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CONFERENCE
on
THE SUN IN THE SERVICE OF MAN

PREFATORY NOTE

Of the quarter million brightest stars, forty thousand have spectra like the sun's. The astronomer's devotion to that particular star arises, therefore, in part from its guidance into the astronomy of the sidereal universe. It is an excellent sample and useful to those who would know stars. There is nothing atypical about it. It falls in the midst of several sequences—temperature, mass, color, relative speed—and it is neither in the nucleus of our galaxy nor at the extreme edge.

Aside from its cosmic advantages, the sun's nearness to the earth makes it available to the astrophysicist as a cosmic furnace wherein the operations of high-temperature physics, chemistry and meteorology can be minutely studied. In the solar corona, for example, the atoms of iron, nickel, and other elements are stripped of their outer electrons; they are, in fact, ionized beyond the present possibilities of terrestrial laboratories. In the eruptive prominences and polar-zone spicules extraordinarily high velocities are recorded; in and around sun spots powerful magnetic fields are measured. Naturally these turbulences and radiations at the sun's surface, and in its higher atmospheres, have influence far out in space. The effects are felt in the atmosphere of the earth. And under the atmosphere, the radiation is vitally important thermally and photosynthetically. Light and life depend upon solar radiation. In partial balance of the servile parasitism of man on the light of the sun, we seek to turn the tables and make the sun the servant of man.

The terrestrial effects and uses of solar radiation immediately bring the astrophysicist into conference with those who study the earth's gaseous envelope and with students of terrestrial energy supplies. Ionospheric and meteorological investigators pay proper respect to the sun, but the heat engineer and the botanist are most concerned. How we can best capture, store, and use the solar energy is the botanical and engineering problem.

Dr. Godfrey L. Cabot of Boston has long been aware of the importance of investigating the storage of sunlight in plants, and the efficient storing and utilization of solar radiation in non-biological ways. The research foundations set up by him in the Massachusetts Institute of Technology and at Harvard have been

important centers for research in the mechanical and botanical problems of captured sunlight.

The Conference on "The Sun in the Service of Man," arranged for February 24-25, 1951, by the American Academy of Arts and Sciences, served to bring together the workers of these two Cambridge groups, as well as the solar astronomers, the meteorologists, and others from the Boston area and elsewhere. The five sessions of the Conference were of great benefit in orienting the specialists in the general field of solar problems, and by instigating new investigations.

The fifteen papers read at the Conference on the 24th are collected in this brochure. The Academy's Conference Committee, Hoyt C. Hottel of the Massachusetts Institute of Technology, Paul Mangelsdorf of Harvard's Biological Institute, and Donald H. Menzel and Harlow Shapley of the Harvard Observatory, has assisted the executive officer of the Academy, Ralph Burhoe, and the Academy's Publications Committee in editorial supervision. The Rumford Fund of the Academy has carried the expense of the Conference and of this publication. Dr. Karl T. Compton of the Massachusetts Institute of Technology and Dr. Marion Eppley of Newport, Rhode Island, presided at two of the meetings.

HARLOW SHAPLEY
Chairman of the Conference

PART 1

THE BIOLOGICAL UTILIZATION OF SOLAR ENERGY

PAUL C. MANGELSDORF
Chairman

THE EFFICIENCY OF BIOLOGICAL PHOTOSYNTHESIS

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Photosynthesis is the process by which sunlight converts water and carbon dioxide of the air into organic material in growing plants with the help of the green chlorophyll. The chemical reaction is written

$$CO_2 + H_2O + \text{chlorophyll} + \text{light} = (H_2CO) + O_2 + \text{chlorophyll}$$

The (H_2CO) represents a unit of a carbohydrate such as sugar. Many other materials are formed also in the plant by other reactions which follow this primary reaction. The whole food supply of the world for man and animals has always been completely dependent on photosynthesis. Furthermore, most of the fuel for heating our buildings and operating our engines comes from photosynthesis, since all of our coal, oil and gas come from organic material produced by photosynthesis millions of years ago and stored conveniently for our present use. These supplies of fuel are exhaustible and will probably be used up in less than three thousand years, and they will be practically irreplaceable. The efficiency of photosynthesis is therefore a matter of importance which calls for a great deal of fundamental research. It is indeed strange that when such enormous expenditures have been made on the improvement of agriculture, such negligible support has been given to photosynthesis which is the foundation of all agriculture.

The farmers of the present are growing crops at an efficiency so far below the maximum which may be obtained under optimum conditions in the laboratory that the actual value of this maximum efficiency seems comparatively unimportant. But in the future, with an increased population to feed, farmers may be interested in knowing how much they might conceivably get from agricultural crops under the best conditions. There is another reason for desiring to know the maximum efficiency in photosynthesis, inasmuch as it can be used as a useful criterion for distinguishing between the many different photosynthetic mechanisms which have been proposed and will be proposed.

If chlorophyll were not known to an isolated scientist, the conversion of carbon dioxide and water into organic material would appear impossible because, in the first place, carbon dioxide and

water are transparent to sunlight, and it is one of the first principles of photochemistry that unless light is absorbed there can be no chemical reaction. In the second place, it can be easily calculated that the energy of the sunlight is not of sufficiently high intensity to bring about the reaction of carbon dioxide and water. Three or more photons of radiation must collide simultaneously with a molecule of carbon dioxide and a molecule of water in order to obtain sufficient energy for a single direct reaction. Such a multiple collision is improbable. Furthermore, the utilization of low-energy photons to bring about a high-energy reaction has not yet been accomplished *in vitro* in the laboratory. Nevertheless nature has been combining carbon dioxide and water in the presence of chlorophyll and sunlight from the beginning.

When a carbohydrate is burned with air, it produces carbon dioxide and water and evolves 112 kilocalories of heat per gram atom (12 grams) of carbon. If one proposed to reverse the reaction and combine carbon dioxide with water to give a carbohydrate and oxygen, it would be necessary to supply at least 112 kilocalories. The actual amount needed for activating this reaction may be considerably more than 112 kilocalories, but it has to be at least this much. The energy in a quantum of radiation depends on the wave length of the light, and in the case of red light the energy is 40 kilocalories for the 6.02×10^{23} photons which correspond to a gram molecule. In other words, we are proposing to make 40 kilocalorie-photons do a job which takes as a minimum 112 kilocalories. If three photons could do the job, the efficiency would be $\frac{112}{3 \times 40}$ or 92 per cent; and if four photons were effective, the efficiency would be $\frac{112}{4 \times 40}$ or 70 per cent. If eight photons are required, the efficiency is 35 per cent. Although 8 x 40 kilocalories would be required to produce a gram molecule of organic material, only 35 per cent of this energy would be evolved when the material is burnt. Theoretically, short ultraviolet light could supply energy sufficient for 112 kilocalories and in fact carbon dioxide and water can be combined with very short ultraviolet light, but plant life is damaged by short ultraviolet light and anyway the amount of such light in sunlight is negligible.

The energy utilized in photosynthesis can be determined by measuring the amount of light energy with a thermopile which has been calibrated with a standard lamp, and the product of

photosynthesis can be dried and burned in a calorimeter to determine the amount of heat stored. It is more common however to measure the quantum yield, i.e., the number of photons absorbed per molecule reacting. The number of photons is obtained by dividing the energy of one photon into the total energy absorbed, and the number of molecules of oxygen evolved or carbon dioxide consumed is obtained by chemical or physical analysis.

Energy measurements in photosynthesis are complicated by the fact that living plants and algae are respiring constantly, taking in oxygen and giving off carbon dioxide in the direction opposite to photosynthesis. Accordingly, a correction has to be made for respiration in all measurements of photosynthesis, and this correction is subject to uncertainty. It is generally assumed that respiration goes on at the same rate in the dark as it does in the light.

Warburg and Leithauser in 1923 were the first to make fundamental quantitative measurements of photosynthesis. They used red light of measured intensity and determined the rate at which oxygen was evolved by algae (chlorella). Making use of a Warburg manometer for the evolution of gases, these investigators reported that four photons of red light are required to make one carbon dioxide molecule combine with one water molecule in photosynthesis, giving an efficiency of 70 per cent in energy storage. These measurements were accepted and went unchecked for ten years.

Measurements of the energy efficiency of photosynthesis in growing algae have been in progress at the University of Wisconsin for nearly twenty years, and these researches have shown that under normal conditions eight to ten photons are required to cause the reaction of one molecule of carbon dioxide and water giving an energy storage efficiency of 28 to 35 per cent when red light is used. In these experiments many different techniques have been employed. Oxygen and carbon dioxide were measured by micro-gas analysis; the oxygen was measured by chemical titration and a special method was devised for measuring dissolved oxygen electrically with a dropping mercury electrode. Standard manometers were used also. In an entirely different approach, the algae were placed in a micro photo-calorimeter in which both the light absorbed and the heat evolved in the algal suspension were measured electrically. It was found that at least 80 per cent of the absorbed radiation was evolved as heat and so not over 20 per cent could have been stored up as chemical energy.

The methods of culture, the influence of nutrients, traces of various elements, and the age of the algae were varied over wide ranges, but the empirical maximum efficiency was always between eight to ten photons per molecule of carbon dioxide reacting.

Emerson and Lewis at the Carnegie Institution at Stanford University carried out an exhaustive research and decided that about 8 photons per molecule was the normal maximum, although under certain abnormal conditions the manometer could be made to give a temporary reading corresponding to 4 and even less than 3 photons per molecule. Rieke, using a manometric technique, reported approximately 8 photons, and Arnold, using a calorimeter, reported about 8 photons. The American researches through 1947 are recorded in the book, "Photosynthesis in Plants," edited by Franck and Loomis and published in 1949 by the Iowa State College Press. More recently Warburg and Burk, however, have carried out further researches at Woods Hole and at Washington and continue to report the original high efficiency of four photons per molecule.

All would agree that photosynthesis can be accomplished with 8 photons per molecule, corresponding with red light to an energy efficiency of 35 per cent, but Warburg and Burk believe that it can be accomplished also with 4 photons per molecule corresponding to an efficiency of 70 per cent. The discrepancy cannot be traced to the standard radiation measurements, because they have been cross-checked with an actinometer developed by Warburg and Gaffron. Several different types of algae and even diatoms have been used and the conditions of nutrient solutions and growth have been varied over wide ranges. The manometric methods as used by Warburg involve the total absorption of light and there is a wide variation of light intensity, those algal cells at the back of the reaction chamber receiving very little light. Scattering of light on the other hand reduces the accuracy of light measurement when the algal cells are diluted so as to allow more uniform distribution of the light. The manometric methods which depend on the measurement of total pressure have potential sources of uncertainties because the carbon dioxide and oxygen are not measured specifically. Extensive researches are now in progress which should permit the rapid and simultaneous measurement of both carbon dioxide and oxygen. The manometric method depends on the relative solubilities of oxygen and carbon dioxide and it is necessary that equilibrium between the solution and these two gases be established very quickly. Such

rapid establishment of equilibrium is not easy. Emerson has proved that under certain conditions a carbon dioxide "burst" can be released when algae are exposed to light after a resting period in the dark. The first products of photosynthesis may include partially reduced organic materials which are easily photo-oxidized back to carbon dioxide in the light. Emerson points out that this burst of carbon dioxide under certain circumstances may be read on the manometer and erroneously calculated as oxygen, thus leading to an abnormally high rate of photosynthesis. In alkaline solutions from which no carbon dioxide can escape, Warburg obtains a maximum value of 8 photons per molecule, but he contends that the reason for the low efficiency is that the algae do not develop at their maximum efficiency in an alkaline solution.

For those who get about 8 photons and a maximum energy efficiency of 35 per cent, the burden of proof lies in showing that their algae are living in full vigor with optimum environmental conditions. For those who get approximately 4 photons, the burden of proof lies in showing that the methods of measurement are valid and that the manometric data are correctly interpreted. All investigators of photosynthetic efficiency have the difficult task of showing that their measurements are not concerned with a temporary or pathological condition, but that they apply to normal, continuing growth. The theoretical limitations of energy efficiency have not yet been worked out, except that more than 100 per cent is impossible and any measurements giving appreciably less than 3 photons per molecule are obviously in error.

Progress is being made in understanding the mechanism by which carbon dioxide and water are converted into carbohydrates and other organic materials. Chlorophyll has intense absorption bands in the blue and in the red, but in thick layers it absorbs all the visible light below about 7000A. Experiments have shown that all the photons absorbed are about equally effective, whether the light is blue, green or red. The chlorophyll molecule becomes activated and then transfers its energy of excitation to a water molecule which then releases a hydrogen atom. The hydrogen then reacts with carbon dioxide to give a partially reduced compound. A second molecule of chlorophyll activated by light releases another hydrogen from water, which reduces further the partially reduced carbon dioxide. In this stepwise fashion, it is possible to use several low-energy photons to bring about an over-all chemical reaction which requires a larger amount of

energy than is contained in a single photon. Some intermediate steps are undoubtedly present which evolve energy and so a total of eight to ten photons seems to be required under optimum conditions. A great variety of organic compounds is produced by this stepwise reduction of carbon dioxide such as acids, carbohydrates and proteins, and many of them are of only transitory existence. They are being studied effectively at the Universities of California and Chicago and elsewhere with the help of radioactive carbon which is used as an isotopic tracer.

Let us consider next the extent to which this laboratory photosynthetic efficiency of 35 per cent can be approached under realistic, large-scale operations in the form of agriculture. A square foot of land in the United States receives on the average about one kilocalorie[1] per minute of solar radiation, and this continues roughly for about 500 minutes of the day. There are about 42,000 square feet in an acre, and so we have about 21 million kilocalories of heat from the sun per acre per day. About half of the solar radiation can be taken up by growing plants; the other half is in the form of invisible infra red radiation which is not absorbed by chlorophyll. Assuming an efficiency of one-third, it is seen that one-half of one-third of 21 million kilocalories or about 3½ million kilocalories might be stored up by growing plants under optimum conditions. Considering that sunlight contains light other than red, that the activation energy may be more than the 112 kilocalories and that more than 8 photons may be required, this estimate of one-third efficiency and 3½ million kilocalories of stored heat per acre is probably too high.

In actual agricultural practise, the average annual corn crop of the United States of 33 bushels per acre amounts to less than two tons of organic material per acre per year—about a ton of corn kernels and another ton for the stalks, leaves, cobs and roots. With hybrid corn, rich land and fertilizer and good growing conditions, it is possible to grow 100-bushel crops with a weight approaching 5 or 6 tons per acre. A fresh, rich silage crop in Wisconsin weighs eight tons per acre, but on the dry weight basis, it amounts to 2½ tons per acre per year. Wheat and hay give of the order of one ton per acre per year. If scientifically forested after a ten-year growth, an aspen forest in northern Wisconsin could give two tons of wood, leaves and twigs per year, and algae in some Wisconsin lakes produce organic material at the rate of about two tons per acre per year. Sugar cane in Hawaii, growing the year round, can give about 40 tons of total dry organic material per acre per year.

Organic material such as sugar or wood gives off about 4 kilocalories of heat per gram when burnt in air, or roughly 3½ million kilocalories per ton. We have seen that 3½ million kilocalories per acre per day is a reasonable value for the storage of an acre of sunlight as calculated on the basis of experiments with algae grown under optimum laboratory conditions. On this *theoretical* basis, one ton of dry plant material could be grown on an acre of land in a day, each ton storing 3½ million kilocalories to be released on combustion. Unfortunately, however, this high efficiency cannot even be approached in agriculture. There are several explanations. For these high, optimum yields, conditions are arranged so that there is an ample supply of water, fertilizers and all inorganic and organic materials necessary for full nutrition, the temperature is kept at an optimum, carbon dioxide is introduced so as to give one hundred times as much as the three-hundredths of one per cent which is found in ordinary air, and the light intensity is kept low. In bright light there is photo-oxidation of the partially-reduced organic intermediates first formed in photosynthesis and the over-all efficiency decreases considerably. Much more than 8 photons of light is required for the reduction of a molecule of carbon because some of the photons undo the work of photosynthesis produced by the other photons. It is partly for this reason that luxuriant plant growth occurs in the long summer days of the polar regions even though the intensity of sunlight is much less than in the more tropical areas. Moreover during the early stages of growth the leaves do not cover the entire ground and not all of the acre of sunshine can be utilized. It is clear then that the one-ton-per-acre-per-day cannot begin to be approached in ordinary agriculture. On average agricultural land in the temperate zone, two tons of organic material is produced, not in a day but in a summer season of perhaps 100 days. It is of the order of two per cent of the material which could be grown theoretically if all conditions were as favorable as those under which algae can be grown in the laboratory. However the two tons of product would give back on combustion only one-tenth of one per cent of the total *annual* solar radiation (2 x 3.5 million divided by 365 x 21 million is approximately 0.001 million).

It may be concluded that nature is remarkably efficient in conserving the energy of the sun in photosynthesis and that the farmer does a reasonably good job in practical agriculture within his limitations of low carbon dioxide and high light intensity. Agricultural research has made tremendous strides in improving

crop yields and much more can be accomplished, but if the world gets really pushed to grow enough food and fuel, more radical approaches should be considered, such as the tank-farming of algae, fertilized with carbon dioxide. In such ways, it might be possible to increase the yield per acre far more than can be expected from standard methods of improving present agricultural crops, and eventually to utilize land that is unsuited to present agricultural methods. Genetic studies, too, should be undertaken to develop algae and plants which will have a high photosynthetic efficiency in intense sunlight, and engineering investigations should be directed toward the growing and harvesting of algae on a large scale. Long-range research on photosynthesis deserves much more attention than it has received.

[1] One kilocalorie is about equivalent to the heat evolved in burning half of a small wooden match. In the United States each person eats food equivalent to about 3,000 kilocalories per day and on the average uses fuel for power and heat at the rate of about 150,000 kilocalories per day.

POSSIBILITIES OF PHOTOSYNTHESIS IN LOWER PLANTS

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There is a line of reasoning which leads one inevitably to a utilitarian consideration of the photosynthetic possibilities of lower plants. The underlying premise is that the world needs food, much more food than it can now produce. It needs twice as many *original calories,* i.e., calories in the form of plant substances, within a decade, if that is possible, and still more later.[1]

What principal factors hold back the increase in harvests? Why is not our present knowledge used to fulfill these needs? Everyone recognizes that basically it is the lack of capital, inadequacy of education, ineffective social organization, and a shortage of technicians which together retard most food producing areas. For a given region one or more of these factors will be critical and progress-determining. However, opportunities exist for by-passing difficulties encountered on the social and economic level, so let us assume, for the moment, that the difficulties will be resolved. Even then some parts of the world would be unable to meet their food requirements.

For them the efficiency-determining process lies in the system of agriculture itself. In most crop plants, such as maize and potatoes, a moderately efficient photosynthetic machine works for only about two months of the year, the remainder being greatly reduced by incomplete land coverage or the loss of leaf pigments upon maturation. During the period of maximum growth one finds that the soil itself often stands in the way of the movement of ions to the root ends. Crops such as sugar cane, which maintain virtually full coverage of the soil and have a long growing period, achieve more than double the yield—if sufficient fertilizer and water are conveyed to the roots. However in sugar cane, as with other crops, half or more of the yield has no market value and is burnt, dumped, or plowed under.

This quest for maximum efficiency for converting solar energy into foodstuffs has led to a large-scale enterprise, the sugar estate and refinery, which exploits land, water, sunlight, and fertilizer. The study of higher plants offers no more suggestions which lead to markedly improved yields. Somehow one must escape from the wilting at midday due to excessive transpi-

ration, from the slowness with which ions are transported to the leaves, and from the low concentrations of carbon dioxide in the accessible atmosphere, particularly when the air is still. At this most advanced stage agriculture achieves less than a tenth of the efficiency demonstrated to be feasible for the photosynthetic process under ideal laboratory conditions.

For really improved performance one must look for circumstances where photosynthesis is burdened by the least amount of parasitic life and is required to create a minimum of structural materials such as stalks and roots. Then it would be stripped of virtually all functions but those needed for the reproduction of chloroplasts. In this manner yield might be further increased, but at the expense of adaptability.

These conditions can be found in the microscopic, preferably unicellular, algae. With algae one can provide carbon dioxide, water, and the various ions at optimum concentrations, and one can maintain the temperature at the point of peak efficiency. Then it is only the supply of light which would become the determining factor. Under these thoroughly optimal conditions, but still depending upon the sun, it is conceivable, on the basis of present knowledge, that 20 per cent of the solar energy absorbed by the plant pigments would be converted into chemical energy in the form of dry matter.[2]

Obviously whatever cost and care may be necessary to obtain this 20 per cent figure, the expense would greatly exceed that which would be feasible for large-scale utilization. A whole series of constraints arise which profoundly affect the choice of feasible processes for culturing, handling, and consuming the algae that might so be grown. A question worth exploring is the efficiency that might be expected once these criteria of feasibility are met.

The most fundamental of these constraints are to be found in the scarcity of natural resources. For water and the various minerals required there cannot be too much complaint, because in algae culture and subsequent processing the losses of water, phosphorus, nitrogen, etc., are likely to be insignificant as compared to those involved in any kind of agriculture. Where water and fertilizer are scarce the culture of algae would be more efficient than any alternative use, except possibly a few unexplored areas of hydroponics using higher plants.

With carbon dioxide a wholly different situation is encountered. Optimum photosynthesis in strong light appears to require carbon dioxide at concentrations 20-150 times its normal concentration in air. The increases in growth rate resulting from

ready availability of carbon dioxide may multiply the yield from two to five times over what is possible with atmospheric concentrations. The world has hardly thought of carbon dioxide as a resource, so there are as yet only a few indications of the size of the reserves and the cost at which such carbon dioxide might be available to an installation. If a bacteria-free, sulfur-free, dilute stream of carbon dioxide costs as little as one cent a pound, net, delivered, then this factor alone will be far more important than all other raw material costs.

It is not the total supply of carbon dioxide which is in doubt. Harrison Brown has estimated recently that about 10^{22} grams of carbon are locked in sedimentary rocks[3] while Anderson and Libby have determined the reservoir of carbon in active exchange at the earth's surface as being around 10^{19} grams.[3] These quantities should be compared to annual world food needs which run to around 10^{15} grams for men and essential animals. Extraction from the major reserves, however, requires the expenditure of a considerable amount of energy to release the carbon dioxide. These resources should be measured henceforth in terms of energy cost or money costs so that those sources which are too expensive will not be included.

Another set of constraints is introduced by the choice of organisms. When conditions are optimum for obtaining maximum dry weight yield, they are simultaneously optimum for reproduction. The product therefore consists of organisms which are young and vigorous, with a minimum of food storage materials and waste metabolic products. They are perhaps 50-70 per cent protein, 5 per cent nucleic acids, 10-20 per cent sugars and metabolic intermediates, less than 1 per cent lipoid, 3-6 per cent pigments, and about 5 per cent mineral; the remainder may be miscellaneous polymeric carbohydrates. There are possibilities of altering this composition somewhat, but every suggestion to date has involved a considerable loss in photosynthetic yield along with other difficulties. A high carbohydrate content, similar to potato, rice, or cassava, does not appear to be likely, at least on the basis of presently understood algal physiology.

If algae are to accumulate fat Spoehr has shown that reproduction must be curbed and a relatively mature form cultivated.[4] Under these conditions the organisms are more sensitive to contamination with bacteria and molds. The fats obtained are highly unsaturated and are not too desirable for human consumption in their natural form.[5]

Some of the blue-green species, especially among the *Nostoca-*

ceae and the *Rivularaceae,* are able to fix their own nitrogen[6]—a highly advantageous property. The culture of these organisms, however, is still less flexible and the composition is less variable than for the alternatives which are scattered broadly over several phyla. Experience thus far suggests that blue-greens are also more susceptible to contamination by bacteria.

A third set of constraints is introduced by the characteristics of the process and the necessary equipment. All the conditions so far set down dictate continuous flow rather than batch operation. The continuous flow process permits the ready maintenance of optimum population densities, carbon dioxide availability, and nutrient ion concentrations. It also offers a convenient procedure for harvesting and lower equipment costs per unit of product. In such a process an algal dispersion in nutrient medium would be circulated while exposed to sunlight; the growth increment would be continuously harvested and the nutrient solution replaced as it is consumed.

An efficient continuous flow process requires that there be no abnormally slow steps starting from the procurement of the raw materials all the way to the disposal of the products. Organisms with reproduction times greater than 36 hours are likely to cause trouble for the adjustment of conditions to the photosynthetic optimum, while those with duplication times of 12-15 hours are more desirable. Use of all the principal products and by-products obtained must also be emphasized because the accumulation of a pile of organic waste can quickly become an embarrassment.

Extremely little thought has been directed as yet to the form in which algae would be shipped from such an installation. A spray-dried powder might be suitable as a cattle food, or a component in chicken mashes, substituting for alfalfa leaf meal. Such an end-use, however, means that only 10-20 per cent of the food value reaches the human consumer. Better techniques need to be worked out for converting raw young algae into foodstuffs suitable for human consumption. Very likely the finishing processes may involve biochemical separations, such as the extraction of pigments, blanching, hydrolysis, browning, blending, fermentation, or curing with smoke, salts and molds. In its final form the product might be shipped out as powders, sauces, soups, wafers, sausages, pickled hors d'oeuvres, cheeses, beverages, etc. The overall process would in many instances decide which of these products is feasible as an adjunct to the harvesting stage and which would best be carried out in small industry closer to the market.

A fourth group of constraints upon the use of algae for the capture of solar energy are those set by the cultural patterns surrounding food, fiber, and fuel consumption. Even the imaginations of scientists are prisoners of culture, and so but few experimenters have ventured to taste their products. Those who have consumed freshly growing young algae report a mild grass-like flavor. The texture is, of course, that of a soup or a soft pulp. This is not an American's concept of a desirable food, nor that of any other sizable culture in the world.

Experience shows that it is not practical to introduce a new foodstuff as an emergency ration in a famine area. Too frequently the people classify the material as an equivalent to tree-bark and boiled grass, which are also resorted to in a famine but are discarded as soon as traditional foodstuffs return. Certainly this psychological association is as responsible for the dislike and unpopularity of food yeast in Europe and the Far East as all other factors involved.

A more suitable approach would be to survey the culture and determine what processed foods have evolved over the past centuries, especially those which have found general acceptance as luxuries or are known as foods only available to the middle and upper classes. Some of these (pressed duck, for instance) could never be imitated, but others, such as the sauces, some of the special porridges made from soybeans, and almost any slightly alcoholic brew are likely to find acceptable substitutes derivable from algal components. In general, the regions in which agriculture has been firmly established have sufficient foods and dishes which might successfully be substituted with algal products, especially in the urban centers. However, livestock-raising and food-gathering tribes will find very few of the range of possible products to their liking.[7]

The selection of prestige foods for imitation is important because then the introduction of new products would be associated with improving social status and prosperity rather than hard times. Expanding algal production is then likely to follow increasing social acceptance.

The increasing demand for fibers might possibly provide a market for some algae, particularly the protein and alginic acid components. The current prejudices in favor of wool and cotton are breaking down very rapidly in the face of high prices. The overall world need for fibers, however, is only a few per cent of the need for food.

After food and fiber, many peoples in the less developed areas

require a new source of *fuel*. The prospective costs of growing one's fuel would be quite high. However, countries which need to resort to cow-dung, at present, as a source of household cooking fuel might find it convenient to develop a briquetted, carbonized product from algae resembling charcoal.

Of the four sets of constraints upon the design of fully successful schemes for utilizing photosynthesis, this last is the most complex and unpredictable at the present time. The cultural factors are not likely to play an important part in the first production units brought into operation, but for subsequent expansion they would certainly weigh more heavily than other limitations.

What types of processes are likely to be feasible under these circumstances? What compromises between efficiency and economy need be struck? Obviously only a bare beginning has been made on the engineering so that process designs must remain speculative for the moment, but some of their novel features are already becoming apparent. Three examples are chosen here which suggest the variety of possibilities which are opening up at present.

I — Chlorella

Biologists have investigated several species of *Chlorella* more thoroughly than any others among the lower plants. Optimum nutrient concentrations for growth have been ascertained, and the photosynthetic yield at 100-500 foot-candles is as high as any species known. *Chlorella* require an atmosphere containing 5 per cent CO_2 in order to attain this maximum efficiency. Their feeding value appears to be little different from that of other plant proteins now in wide use.

Retaining the 5 per cent carbon dioxide atmosphere requires a closed system (plastic films seem to offer the cheapest cover that will permit the entry of most of the sunlight). A liquid suspension only a few centimeters thick is sufficient to absorb all the useful light and still maintain a satisfactory gas exchange. The total quantity of organisms exposed to the sun would be adjusted according to the amount of light received and the surplus would be harvested.

The unit operations involved, to revert to a chemical engineer's terminology, include a liquid circulation system covering broad expanses of flat terrain, a mixing unit for making up losses of ions in the nutrient solution, an aerator, a gas purifier and sterilizer, several flotation units or centrifuges, used in series in order

to scrub the nutrient solution from the cells, one or more extraction units to remove plant pigments, and perhaps a spray drier or a fermentation unit at the final stage. This is a process which could supply some of the immediate needs of Japan and requires techniques, materials, and resources which are available in Japan to a limited degree. It is not unreasonable to project a net yield of protein of 15-20 tons, dry weight, per acre per year in the Japanese climate from such a design.[8, 9]

II — Blue-Greens

In areas of temperate climate, where little or no synthetic ammonia is available, the prospects of growing nitrogen-fixing blue-green algae appear to be most favorable. Thus far only a few filamentous species have been found to be nitrogen-fixing, using unambiguous isotope methods, but some of the *Anobaena* species and *Gloeotrichia echinulata* appear to be sufficiently dispersible. A nutrient medium for blue-greens is somewhat different than for *Chlorella*, and the optimum pH is around 10 instead of 5-6. Partial amino-acid analyses of proteins in actively growing blue-greens indicate that they should be suitable food materials.[10]

Too little is known about the physiology of these organisms to put forward any more explicit description of a large-scale process, but, if laboratory data are any criterion, it appears that a feasible economic target would involve the fixing of two tons of nitrogen per acre per year. The process designs employing blue-green algae would need to be less elaborate and expensive than that described for *Chlorella*. This is aided by the high pH which might permit economic use of carbon dioxide from the atmosphere, and also by the observation that bacteria do not seem to inhibit growth.

III — Mixed Culture

A very interesting possibility has opened up recently for growing mixed, interdependent cultures under carefully controlled conditions. In a tropical environment the *Euglena* were found to achieve dominance when a soluble commercial fertilizer was used for the nutrient medium. This technique, when developed, may turn out to require a number of trained native operatives and depend much less upon instrumentation and industrial process equipment. The yield would undoubtedly be less than for pure cultures, but there is a good chance that more fat and car-

bohydrate could be obtained which would permit a greater variety of end-uses.[11]

It will be noted that these three examples suffer most from a lack of fundamental information in biochemical and more strictly biological areas. These gaps are filling in slowly but progress has thus far not been very rapid. By now, however, a stage has been reached where there is a good prospect for economic utilization, particularly outside of food surplus areas such as North America and Australia. This suggests that the remaining questions may be solved by empirical, engineering-oriented investigations. Technology seldom awaits a full theoretical and experimental elaboration of the underlying phenomena, but usually precedes it by many years. The uncertainties are balanced in practise by large safety factors. As the fundamental biological sciences progress it is anticipated that they will establish the amount of waste involved in employing such large safety factors, thus bringing about changes in the first operating designs and greater efficiency of subsequent installations. Fundamental research in these fields could then, with very little delay, result in improved human welfare, as well as carry out its traditional function of extending the boundaries of knowledge.

In summary, it might be said that unicellular algae promise to utilize sunlight economically with an efficiency in the neighborhood of 5-10 per cent. Although there are many constraints operating which limit the development of large-scale facilities, there are several process design possibilities which look quite promising at the moment.

[1] The United Nations Food and Agricultural Organization in *World Food Survey* (1945), and *Survey of World Conditions and Prospects—1949* (1950) outline in a somewhat debatable, but nevertheless useful, manner the current needs, the goals, and the progress.

[2] As far as I am aware, there has as yet been no investigator who abandoned his convenient fluorescent lamps and attempted the experiment!

[3] Anderson and Libby, *Phys. Rev. 81*, 64 (1951).

[4] Spoehr and Milner, *Plant Physiol. 24*, 111 (1949).

[5] Milner, *J. Biol. Chem. 176*, 813 (1948).

[6] Fogg, *Endeavour 6*, 172 (1947) and communication from R. H. Burris.

[7] I have carried out surveys based upon interviews with graduate students from all parts of the world aimed at getting evidence of the willingness of the poorer people they knew to accept new foods. Ice cream is the most

widely popular of all processed foods, but even it would be met with suspicion by some of the more isolated Moslem peoples.

[8] For the basic information underlying this description and those following, I am indebted to many biologists scattered over the United States and Great Britain, but the help of Paul Cook of the Stanford Research Institute and Jack Myers of the University of Texas has been especially rewarding.

[9] This design might be very advantageously linked with a high temperature pebble pile for reacting the nitrogen with the oxygen in air. The combusted gases from heating the pile and the limestone used for dissolving the nitric oxide together would provide about 3 CO_2 molecules for every nitrogen atom fixed. This is not far from the proportion which is required for *Chlorella*. See GILBERT and DANIELS, *Ind. Eng. Chem. 40,* 1719 (1948).

[10] WILLIAMS, A. E., M.A. Thesis, University of Wisconsin, 1951. Profs. Burris and Skoog and Dr. Gerloff were also helpful, as was Dr. Fogg at University College, London.

[11] This approach is suggested by the work of Jorgen Jorgenson, Laboratorie de Chaulmoogra, Maiquetia, D. F., Venezuela.

PHOTOSYNTHETIC ENERGY VIA AGRICULTURE

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There never has been a time in human history when all of the world's people had enough to eat. Primitive man spent most of his time searching for his next meal. The development of agriculture, some eight or ten thousand years ago, was the foundation of civilization. Agricultural production released men from the search for food supplies, so that part of the population could devote their time to industry and the arts and sciences. Today the proportion of the population released from food production is a good index of modern civilization.

In spite of the great advances in agricultural science and technique during the past century, two-thirds of the world's people live little above subsistence levels. Paradoxically, the countries which devote the most manpower to agriculture have the poorest diets. Nor is this situation necessarily due to low productivity per acre. The Chinese farmers produce nearly twice the yields per acre as do American farmers.

The food shortages of the world must be viewed from the standpoint of both production and consumption. At present food production is not keeping pace with population growth in most of the world. The world population has increased nearly fourfold during the past 300 years, and at present is growing at the rate of nearly one per cent per year. Every decade the world must provide for 200 million more people. Yet man lived and multiplied for 40 or 50 thousand years before the world population reached half a billion people little more than 300 years ago.

The unprecedented growth of the human species during the past few centuries is due to the control of the death-rate without a corresponding control of the birth-rate. Primitive man had to have a high birth-rate to compensate for a high death-rate. Modern science has reduced death-rates in the modern western nations to about a third of those prevailing at the dawn of history. Yet there is no evidence of any significant decline in man's natural fecundity. As a result there has been explosive population growth in much of the world.

Only the modern western nations have made the Demographic Transition—the transition from a high birth-rate high death-rate culture with low living standards, to a low birth-rate low death-rate culture with high living standards. Dr. Frank Notestein of Princeton has divided the world into three demographic groups as shown in Table 1. In Group 1, the Demographic Transition is essentially completed, and population growth is coming to an end. In Group 2 areas, birth- and death-rates are declining, but population growth is still rapid. In Group 3 areas, birth-rates are still near the physiological maximum, and only high death-rates prevent very rapid population growth. These poor, rural, illiterate peoples have yet to begin their Demographic Transition. The economic and dietary data are from "Point 4."

TABLE 1

	*Demographic areas.**		
	1	*2*	*3*
Population—millions	460	450	1500
Annual income per person	$461	$154	$41
Per cent workers in agriculture	25	50	75
Daily calories per person	3040	2760	2150
Illiteracy	—5%	±20%	±80%
Life expectancy, years	63	52	30
Birth-rate	±20	±30	+40

1. Western Europe, N. America, Oceania.
*2. U.S.S.R., Balkans, Argentina, Japan.
3. Asia, S. and C. America, Africa.

Eighty per cent of the world's people still have to make the Demographic Transition. In making the Demographic Transition the people of European origin have increased sevenfold, and even with an industrial pattern to follow it is doubtful if any nation can make the transition with less than a threefold increase in numbers. Even with a doubling of the populations in demographic areas 2 and 3, the world would have to look forward to providing food, clothing and shelter for more than 4 billion people.

The immediate problem is to provide adequate food and other necessities of life for the present world population of 2.4 billion people. Sir John Boyd-Orr, former chairman of the Food and

Agriculture Organization of the United Nations, has surveyed the present status of production and consumption of food. The data are shown in Table 2.

TABLE 2

FOOD PRODUCTION AND CONSUMPTION

	N. Amer.	*S. & C. Amer.*	*West Europe*	*E. Europe U.S.S.R.*	*Asia*	*Africa*	*World*
Acres per person	3.5	1.4	0.7	2.0	0.6	1.0	1.0
Original calories per acre per day	3,000	3,400	7,500	2,300	4,500	3,000	4,000
Original calories per person per day	10,000	4,600	5,500	4,600	2,700	3,000	4,000

If the entire world were as productive as Western Europe, there would be ample food for the world even with one acre of cultivated land per person. In order to provide United States dietary standards for all of the world's people, the present world production of food would have to be more than doubled. We do not use 10,000 calories per day per person directly, but much of our food is from animal sources—meat, milk and eggs. It takes six or seven times as much land to provide food in the form of meat or milk as it does to provide food directly in the form of cereals or tubers. The Asiatic diet is based almost entirely on cereals and vegetables, and they actually get only about 2100 calories per person per day, because much of the original 2800 calories is lost in storage and processing.

Theoretically it is possible to double the yields per acre in most of the world. Since the first World War, yields per acre have increased at an average rate of about 1.5 per cent annually, due largely to the greatly increased use of fertilizer during the past decade, better farm practices, and the development of better crop varieties and hybrids. If necessary, and if sufficiently high prices were paid for farm products to justify great increases in the use of fertilizers, irrigation and use of marginal land, food production could be doubled in North America. Western Europe has already developed a high production without exploiting soil resources and without excessive use of manpower. In Asia, however, high yields have been attained by intensive cultivation and use of manpower to the extent where returns per farm worker are pathetically low. In the United States less than 20 per cent

of the working population produces more food than we need, but in China, 70 per cent of the people are engaged in agriculture but produce only subsistence diets. There can be no hope for high living standards if most of the population is engaged in producing food for its own consumption.

Dr. Salter of the U. S. Department of Agriculture has estimated the possible increased yields per acre of the cultivated land of the world. By 1960 it should be possible to increase pre-war yields by about 25 per cent in the United States, 30 per cent in China and the U.S.S.R., and 50 per cent in India. For the world as a whole, an increase in yields per acre of about 30 per cent is postulated. In order to attain such yields, Dr. Salter estimates that it would be necessary to increase the consumption of phosphate fertilizer eightfold, and potash 18 times present consumption, plus large increases of nitrogenous fertilizers.

According to Dr. Salter, the pre-war production of food in the world was about 1000 million tons annually. By increasing the yields of land already in cultivation by about 30 per cent, total yields of nearly 1300 million tons of food could be expected by 1960. Allowing for population growth, the food needs of the world are estimated at about 1630 million tons in 1960. These estimates are based upon goals set by the Food and Agriculture Organization of the United Nations. The proposed increase in dietary standards for subsistence areas is at minimum levels with a proposed increase from about 2200 to less than 2600 calories per day per person. Even with these limited goals, the increased production of food postulated from present cultivated land is not enough to meet minimum needs by 1960.

More land must be brought into cultivation. According to F.A.O. and U.N. estimates, the land now in cultivation totals about 2.4 billion acres or about one acre per person for the present world population. The amount of land per person varies greatly—from about 4 in North America to 0.5 acres in Eastern Asia. Dr. Salter assumes that a billion acres of tropical land could be brought into cultivation and would yield nearly 1200 million tons of food, bringing the total world production up to 2460 million metric tons. In addition, another 300 million acres of land in the temperate zone would be expected to yield another 120 million tons of food, or a grand total of more than 2700 million tons of food—far above the minimum needs of 1630 million tons.

The estimates of potential increased yields from present land are conservative, but new tropical land is expected to produce

more than present yields of all land now in cultivation or nearly three times as much per acre. Most tropical areas will produce two crops each year, but the tropics present other problems in crop production. According to Robert L. Pendleton, Professor of Tropical Soils and Agriculture at Johns Hopkins University, "except for relatively very small areas of soils from volcanic ash and recent alluvial soils, most of the soils of the tropics, judged by temperate zone standards, are extremely low in plant nutrient substances and organic matter; nor are most temperate zone methods of fertilization or soil management appropriate."

The rapid loss of organic matter and excessive leaching of plant nutrients in most tropical soils is only part of the difficulty in developing an extensive tropical agriculture. As Clarence A. Mills pointed out, people who live year after year under a blanket of moist heat do not maintain an active life or high vitality. "Physical and mental characteristics change from the dynamic and pushing to a more passive, let-George-do-it type." In the American tropics, at least, the problem is further complicated by political graft and corruption which makes difficult any effective rehabilitation through local government agencies.

But let us assume that Dr. Salter's goals of food production can be attained by 1960, even though there is no possibility that it will be done. Dr. John Black, Professor of Agricultural Economics at Harvard University, in an analysis of Dr. Salter's estimates, makes the following observations—

"Even with all this new land cleared and developed and farmed according to modern practices, the increased supply of meats and pulses would already have been exhausted by 1960, and if the population increased at the same rate after 1960 as assumed for the years from 1935 to 1960, the increased milk supply would be exhausted by 1970, and the increased supply of fruits and vegetables by 1980. After that, any population growth would be possible only by reducing the per-capita intake of milk and meat and living more on cereals, roots and tubers, sugar, and vegetable oils. Even with the diets shifted to cereals and roots and tubers, the food supply would reach its limit within 75 years."

"If anyone wants to take exception to Salter's estimates and say that they are not liberal enough, let him double them. The result will be the same, except that it will be deferred."

"It should now be clear that the two lines of action proposed in the Hot Springs 'Final Act' (of the Food and Agriculture Organization of the United Nations) increasing food production, and increasing the power to buy food, will not be enough—that

adjustment of population to resources is also necessary. Indeed, this is by far the largest part of the problem."

Yet the population problem is not even mentioned in President Truman's "Point 4" program.

In surveying the agricultural possibilities of food production for a hungry world, we have not considered other sources of food and food utilization. Among the more fantastic proposals is that made by J. D. Bernal in his book, *"The Social Function of Science."* He assures us that it should be possible to convert coal, limestone and air into food in sufficient amounts to feed "populations thousands or millions of times that which exist at present." Assuming the dubious advantage of increasing the world population even a thousand-fold, what happens to the thousands of billion people when the supply of coal becomes exhausted? Food production must be based upon renewable resources. If the world's per capita consumption of coal equaled the present consumption in the United States, the world's coal supply would be exhausted in a thousand years.

Food production is not dependent on agriculture, and all possibilities should be explored. Dr. Egon Gleisinger in his recent book, *"The Coming Age of Wood"*, suggests the use of wood products for food, fiber, and power. He estimates that the eight billion acres of the world's forests could produce a ton of wood per acre annually. It is possible to convert wood into sugars and edible carbohydrates for cattle food, but the process is expensive. If the entire world used wood for construction and pulp at the rate of United States per capita consumption, there would be little left for food.

The possibilities of greater photosynthetic efficiency by using algae has already been discussed by Dr. Meier. It has been shown that the production of carbohydrates by *Chlorella* under favorable conditions can be much more efficient than either agriculture or forestry. The problem of converting these algae to edible and palatable forms of food is a difficult one, but production of livestock food and liquid or solid fuel is perhaps more feasible. Yeast production from low cost carbohydrates is already past the experimental stage, yet yeast consumption must be limited to a small part of total dietary needs. The maximum yeast consumption recommended is little more than an ounce per day per person. The cost is said to be about ten cents per pound, but the cost of edible yeast at Boston's leading grocery store is $1.50 for a quarter of a pound.

As our capital resources become exhausted, the world will have

to turn more and more to renewable resources from the farms, forests and waters of the world. We can expect great advances in forestry and agriculture—new hybrids of crop plants and trees which will greatly increase production, more efficient use of soils and fertilizers, more efficient livestock, and the use of vitamins and antibiotics to promote growth. It is possible that microbiology will come to the aid of food production as it has in industry and medicine. But no possible increase of food supply can keep pace with a population arising from a natural primitive birth-rate and a modern death-rate.

ENERGY FROM FORESTS

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There is a considerable body of evidence to indicate that woody plants, particularly trees, constitute one of the world's most efficient biological agencies for the capture of solar energy. Forests now cover approximately one-fourth of the total land surface of the earth, or about 8000 million acres. We can apply factors for volume or space to unit production efficiency in trees, therefore, to produce gigantic figures of quantity. Because forests can, if rightfully managed, be continually regenerated, we can expect to achieve a continuity in the supply of energy not to be found in organic deposits. With these facts in mind, it behooves us to study with great care the productive capacity of forests.

The field of forestry is commonly divided into several parts, each with its subject matter and problems. These parts fall roughly into three groups. The first includes what might be considered the engineering aspects of the field. They are concerned with the evaluation, recovery and utilization of wood. We have seen rapid developments in all of these aspects in recent years, particularly in wood technology. We no longer think of forest products primarily in terms of lumber, paper, fuel and naval stores. We are learning to make a great number of products by the manipulation and rearrangement of wood fibers, or we break down the wood chemically and use its molecules for the production of entirely new substances. A second part of the field of forestry is closely related to the first, and lies in business management. The final decisions regarding wood recovery and utilization, and ultimately with regard to forest policy, are typically business decisions. Allied with them are matters pertaining to private and public administration of forest lands, and to forest taxation and finance. The third part of the field covers most of the biological aspects: the development and management of forests for the production of wood, for the protection of the land and water resources, or for recreation.

A study of the productive capacity of forests could be approached through the engineering and technical aspects of the field. Existing inventories could be tabulated and balanced against new and improved methods of use or the elimination of waste. Most of forestry research, past and current, has been

devoted to these aspects. If we consider forests as a basic source of energy, however—a source that can be depended upon to continue for a long time—the problems of sustained long-term production loom as the most significant in the whole field of forestry, for without their solution the planning of long-continued use has no point. It may be necessary for us to develop a silviculture that will approach agriculture in efficiency and scope.

The development of silviculture requires the solution of both biological and economic problems. This paper will consider primarily some of the biological problems involved, though it will be impossible to do so to the complete exclusion of economic and social aspects. No forest exists in an economic and social vacuum, but here will be considered only the biological potential of land for the production of wood. Having discussed in broad outline the existing status of silviculture, some suggestions will be offered regarding the future course of research in this field.

It may be said in general that our knowledge and techniques in silviculture are far from satisfactory. The reasons for this are many and varied. Except in a few parts of the world such as temperate Eastern Asia and parts of Western Europe, civilized man has always lived with a relative abundance of wood. In many parts of the world he has had to destroy the forests in order to make room for necessary agriculture. In this atmosphere of abundance he has not felt the need, or could not afford, to develop an efficient silviculture. In the most densely populated parts of the Far East, forests have been almost completely eliminated, with no provision for their reinstatement. In Western Europe the demand for wood outstripped the natural supply a comparatively short time ago, and silviculture has been raised there to the highest levels known. Throughout most of the world, however, man still depends for his wood supply upon the exploitation of virgin forest or of second growth forest that has had no management. This is primarily the mining of a natural resource which, though it has the capacity for being renewed, is treated as if it were a non-renewable though relatively inexhaustible material such as oil or coal.

Another reason for man's failure to develop silviculture as rapidly as agriculture has been the fact that there are many substitutes for wood, but there have never been substitutes for food.

Further reason is to be found in the nature of silvicultural research itself. It is of necessity slow because of the slow rate of growth of forests. Since the time of Theophrastus and the

early Maya there have been at least two thousand generations of wheat and corn, enough to give ample opportunity for the study of the relations of these grains to their habitat, and time and materials for the improvement of cultivated strains. There have been in the same period only ten or twenty generations of our common forest trees. Success with agricultural crops has depended to a large extent upon the opportunity for repeated trial and error experiments with the selection of genetic strains, hybridization, and the manipulation of sites. Such experiments have not been practicable with long-lived forest trees, and progress toward the control of forests in the agricultural sense has been kept to an extremely slow pace.

With such slow development the general rule, methodologies in silvicultural research have never been standardized. We have no body of knowledge and method which can be widely applied outside the region in which it originated.

The present status of silviculture is reflected in forestry education. Silviculture as a subject is taught in all forestry schools, and though it is highly developed in some parts of Europe, it has never been more than a minor handmaiden to American forestry curricula. Our schools and their attendant research organizations are heavily weighted toward the recovery of wood from the forests, its properties and utilization, and toward the protection of the natural forests that still exist.

Before going on to a discussion of the capacity of forests to accumulate solar energy, it would be well to mention some of the basic characteristics of forests as biological entities. The first of these characteristics is geographic position. Forests are made up of species of trees, usually of more than one, and often of many species. Each of the species has a geographic range which can be defined by observation. The range of a given forest complex or type therefore is a composite of the ranges of the species that predominate in it. Examples are the spruce-fir forests of Eastern Canada, the oak-hickory forests of the central Appalachian region, and the various phases of the great coniferous forests of the Northwest. These geographic patterns are relatively fixed by causes that are not clearly known. Alterations in them have occurred, but the time intervals involved in the changes run into long periods, such as thousands of years.

Another basic characteristic of forests is that in spite of the relative permanence of large geographic patterns, natural changes in form, species composition, and density are con-

stantly going on within limited areas. These changes are spoken of as biological successions. They are relatively slow, but many are definable with our present knowledge over periods up to a few hundred years in length. They arise from the fact that the existence of a forest type in a given habitat commonly alters the character of the habitat to such an extent that the composition of the ensuing stand will be changed. If we are to understand and use the forests we must of necessity learn what these trends of development are and how the existing forests fit into them.

Such understanding is difficult to achieve because of another type of change which is exceedingly common. This is cataclysmic in nature and is probably of equal importance to slow successional change. Much of our current silvicultural theory and practice has been based upon a concept of continuity and stability in soils and climates. We have realized the destructive significance of fire and pests, and devote much time and money to preventing them. We have some reason to think that we can control these influences. But no one has seriously considered trying to ward off hurricanes, though we now know that the forests in large sections of the eastern United States have been destroyed by high winds three times in as many centuries. Our surface soils have been so much disturbed by the uprooting of trees that they may as well have been plowed at infrequent intervals. Whatever long-range plans we make for the use of forests must allow for such unavoidable catastrophes.

Because the solar energy captured by trees is converted into wood, it can be measured in terms of the volume of wood produced per unit of area and time. We have elaborate methods for computing volume in existing stands of timber, and for computing the rate of increment in growing stands.

We admit at the outset that with existing knowledge we cannot, by emulating the agriculturist, analyze the habitat or site, apply our analysis to the trees available, and arrive at prediction. We therefore revert to the age-old concept of "plant indicators" in the sense that we utilize the trees as integrating systems. For a given area we speak of "site quality," and attempt to measure it by the performance of the existing trees. At best our predictions of yield are only rough estimates, even in what we think of as normal, fully stocked stands. They are most accurate in even-aged stands, and in forests composed of one or a very small number of species. Usually they do not go beyond the existing stands.

The density of a stand is measured by the number of trees per unit of area, or by the total basal area of cross-sections of the trees taken at breast-height. From these figures and from tree heights we can arrive at volume by reference to tables that have been prepared for various species and regions. By plotting these various figures, usually tree height, against age we get a "site index" which can be compared with other indexes from similar areas. If we are reasonably successful in our computations we have measures of volume and increment that can be balanced against probable costs, and the economic feasibility of operations in existing stands can be predicted.

Production potentials arrived at by these means are of short-term nature and can be misleading. A great many of our estimates of site quality at the Harvard Forest, for example, are based upon measurements of nearly pure stands of white pine. The production of white pine lumber on our upland loam soils between 1850 and 1920 was phenomenal. It commonly amounted to 60,000 board feet per acre in sixty-year-old stands. We now know that these white pine stands were in a sense "artifacts" resulting from the abandonment of upland loam soils previously used for agriculture. In spite of every effort to perpetuate them by economically feasible means, they are being succeeded by the native deciduous trees of the region. In these new forests, as far as our present knowledge goes, the total volume produced, even in eighty years, probably will not be over 30,000 board feet per acre.

Before measurements of production potential can be realistic, therefore, we must be able to place existing stands of timber in perspective with regard to their regenerative capacity, their place in natural trends of development, their relation to past and future cataclysmic changes, and their probable effects upon the productive capacity of ensuing stands. If we are to think of forests as long-term producers of energy, it is necessary to calculate far into the future the production rates computed by present methods. We must learn to go beyond existing stands of timber, and determine the long-term production potential of the land and the forests to produce wood.

Even though our prediction of long-term production potential can be little more than a guess, we must be content for the time being with the potential that exists. With our present knowledge of forests and sites, and within the present or foreseeable economic structure, we do not know how to make any great improvement in the potential. Silviculture can show no such

progress in this respect as does agriculture, for reasons that have already been suggested. The agriculturist has no hesitation about trying to improve the site. He removes the natural vegetation, alters the physical, chemical and biological properties of the soil, introduces exotic crop plants, protects them from pests and diseases, and even tries to improve the climate under which they grow. He can do this because the time intervals are short and because, with all his manipulations, he still can predict the outcome with fair accuracy and be confident that the final product will more than pay the costs. The silviculturist has no such control of forest production.

This does not mean that we cannot make some changes for the better in what we recover from existing forests or from potential forest lands. Cleared lands, provided they can be relegated to forests, can be planted to trees. Existing stands can be treated in such a way as to raise the percentage and quality of marketable trees, and perhaps to shorten the time required to produce a marketable crop. By-products of such treatments may be sufficient to pay the costs of the treatments. The total amount of wood actually produced on a given area in a given time is always greater than yield predictions for the final crop would lead one to believe. While the net volume is steadily increasing as the stand approaches biological maturity, a large amount of wood is being lost by the death of suppressed trees. Much of this loss can be captured by properly timed thinnings and improvement cuttings.

Following the harvesting of a mature crop the forest must be regenerated naturally or artificially. European foresters, with their long experience and with relatively simple forests, have been fairly successful at this; but in the New World we have made only small beginnings.

A large proportion of the world's silvicultural activity to date has dealt primarily with the reforestation of cleared land, with the treatment of existing stands for improvement of quality and growth rate, and with the regeneration of existing stands at low cost. These pursuits, and the techniques that have evolved in them, have produced some excellent results and should be continued; but they are badly in need of some fundamental research in the biology and economics of forest production.

In planning silvicultural research we need some realistic point of departure, or "datum plane," from which to begin. The agriculturist finds this in the composite experience of countless generations of his ancestors, wherein it is based upon accumu-

lated knowledge of the behavior of crop plants in relation to soils and climates. In silviculture we do not have such a resource. We are inclined to forget that this great body of agricultural folklore exists and is the real base from which the modern agricultural scientist operates.

Throughout most of the world the harvest of wood is the harvest of a wild crop. We are not far removed from the situation of those ancient proto-farmers who, discontented with having to spend a great part of their time and energy gathering food from wild plants, began to consider how they could concentrate them where and when they wanted them. Nevertheless, we commonly apply modern techniques and assumptions derived from agriculture to our forest problems. We fail to realize that our knowledge of trees and the sites on which they grow will not give us the control that is in the very fabric of agricultural practice. It may be that we should relinquish for a time much of the modern agricultural thinking that tends to invade our research, and revert to the simpler concepts used by our progenitors when they first attempted to domesticate wild grasses. We must find our point of departure in the behavior of natural forests, and our immediate problems center in the rational use of wild populations of trees.

Perhaps we should begin with refinement of our knowledge of the geographic location of forests. We already have the broad outlines of this, but details of sufficient fineness to be usable in actual operations are obscured by previous use or recurrent catastrophe. We must accordingly determine trends of change so that the identity of the natural forests can be unmasked. In practice such a pursuit could be called the ecological classification of forest lands. It should eventually lead to a definition of the natural production potentials which any region affords, for it makes full use of the results of millennia of nature's experiments in adjusting trees to their sites.

Having learned what and where the natural forests are, the silviculturist should utilize all his knowledge and ingenuity to improve the quality and rate of their production of wood. He must learn to harvest them without destroying or decreasing the productive capacity of the forests themselves or of the lands they occupy. If trees are to be planted, species and sites should be brought together so as to give reasonable hope of success. Our landscapes are strewn with fiascos resulting from the hit-or-miss selection of trees and sites for planting. If wood-using industries are to be established, they should be so placed and so organized

that their raw materials will be available not only while the present generation of trees exists, but for many future generations. Existing industries should adjust their use of raw materials to the natural production rates of the forests as soon as these potentials can be determined with reasonable accuracy.

These are immediate problems, the solution of which we can hope for with our present knowledge and techniques. If forests are to continue even at the present level in the service of man, however, we cannot be assured that the existing production potential of lands now occupied by trees will be enough. Perhaps we should look forward to the control of forests, in the agricultural sense, on a world-wide scale. Our remote ancestors domesticated their crop plants without knowledge of morphology and physiology, or of actual relations of the plants to water and nutrients in the soil, or of the mechanisms of inheritance. Although our final problems are still of long-term nature, we should be able to make more rapid progress than we would if we had to continue with such limitations as those under which they labored.

First we must learn much more than we now know about the nature of site, and about the ecological relations of trees and forest communities. In modern forestry much of this comes under the heading of "silvics." It aims at the statement of cause and effect relationships between trees and their environments; and most of its research has been in terms of factors of the environment balanced against the supposed requirements of the trees. Its methods have led inevitably to direct attacks upon these factor relationships, and so to a hopelessly complex dichotomy of purpose. We seem unable to put back together again, by taking thought, what we have taken apart with such abandon, for we have no reasoning with which to integrate the multiple variables involved.

We have, however, integrating agencies in the wild trees themselves. We can use them as such provided we are willing to give up, for the time being, our direct attacks upon cause and effect problems. If we can properly define our natural forest types in terms of their species composition and their geographic position, we will have a framework within which to make comparative studies between the behavior of the trees and the factors of the environment. Coincidences accumulated by such studies, interpreted in the light of all the knowledge we possess, will greatly increase our skill in the design and conduct of experiments.

Having thus broadened our understanding of the wild forests

we can concentrate more intelligently upon controlled improvement. Such improvement can be approached along two lines: through the growing stock of the forest itself, and through the soils.

The long-term use of good management practices should not only raise the quality of the final crop in the present generation, but should tend to raise it for future generations as well. Good practice aims at the selection of elite trees for the final crop, and if these can be made the source of the new generation after harvest, a selection of the best biotypes for future generations should result. The genetic improvement of the forests can also be attacked by more direct means through the selection, hybridization and nurture of elite trees. It should be borne in mind, however, that this will be fraught with great difficulties until our control of forests is considerably farther advanced than it now is.

Much can be accomplished toward the improvement of forest soils by proper manipulation of the cover, and perhaps of the soil itself, at times of thinning and harvest. We are beginning to know a little about the biological and physical balances that exist in the soils, and we know that they are of great significance to the well-being of trees; but we know almost nothing of their control. The physical manipulation of forest soils may prove to be of first importance. It occurs naturally in the uprooting of trees, in frostheaving, in the mass movement of soils on steep slopes, and as a result of fire. Perhaps we shall have to reproduce it artificially. It may be that we shall come eventually to some kind of fertilization, either by direct application or by the artificial encouragement of species that will enrich the soil.

Our ultimate goal is of course a reasonably accurate prediction of, and improvement in, the rate of capture of the sun's energy by trees. With present knowledge the best hope of prediction seems to lie in the study and use of natural forests, and we can, with continued research, expect to make a small amount of improvement in the quantity of energy we can capture in the wild forests. Large improvement can come only when we cease to be dependent upon wild stands, and when we can say that we have domesticated our trees.

INCREASING SOLAR ENERGY CONVERSION EFFICIENCY IN FOREST TREES BY THE APPLICATION OF GENETICS

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The forests of the world represent one of the most important, if not the single most important, agency by which the radiant energy of the sun is converted into a storehouse of products directly or indirectly serviceable to man. The profligate manner in which man has exploited this native wealth without thought for the future, both in the Old World and the New, is a portion of our world's history with which most everyone has been made familiar during the past two decades.

The rehabilitation and maintenance of these important solar energy converters on a high level of production is a gravely complex biological problem intimately intertwined with numerous special local economic and engineering problems. The responsibility for the efficient prosecution of this job lies with the forestry profession; and more particularly with the silviculturists. These are the forest biologists most directly concerned with the study of the nature of forests and forest trees—how they grow, reproduce and in other ways respond to changes in the environment.

The "art" of silviculture had its origin and underwent its early developmental phases in Germany, France, and the Scandinavian countries during the 19th century. With the development of a forest consciousness in most of North America during the early part of the present century, the precepts of the European silvicultural art were transferred to our own country, and an attempt has been made to make them suitable to our own forests. Unfortunately this effort has, in large measure, been unsuccessful. Not only has European silvicultural practice proved to be ill-adapted to many of our forests because of their vastly more complex nature, but for the most part American silviculturists have not yet modernized this heritage of the Old World, which unfortunately has a biological basis contemporary, in some instances, with the biological theories prevailing in the 1850's.

Of all the erroneous 19th century ideas inherited by American forestry that still in a large measure persist, there is perhaps

none that has confused our silvicultural reasoning so much as the concept that taxonomic uniformity of leaves and flowers within a species implies a genetic uniformity in the physiological functions of growth and development as well. The natural and unfortunate consequence of this concept of genetic uniformity is that the bulk of intraspecific variability detectable in the forest is confidently attributed to environmental differences and an effort is thus made to rationalize a silvicultural system of management based on a study and manipulation of the environment alone.

These remarks do not imply that the silvicultural manipulation of the forest environment is wrong and should be outlawed. Indeed, from the practical point of view in forest management, such manipulation of the environment is the most direct, and will doubtless rightfully continue to be the most important method of influencing changes in the phenotypes of forest trees. We must, however, discard the complacent assumption that an intimate knowledge of the physical properties of the soil or the microclimate will in itself, independently, supply the answers to the best method of growing genetically complex populations of forest trees. If logical solutions to the numerous problems confronting the silviculturist are to be solved rationally, we must of necessity adopt methods of research that will in some reasonable manner evaluate results in terms of both the environment and the particular genotypes concerned.

The addition of a new set of variables introduced by recognition and acknowledgment of the genotype does, of course, complicate the experimental approach to silvicultural problems. But the difficulties are by no means hopeless for such experiments may be adequately controlled in one of two general ways: either genetically uniform clonal lines of a local race may be subjected to different environments, or genetically variable representatives of a local race may be subjected to a uniform environment. Combinations of such experiments may be expected to yield a body of reliable local silvical data that will provide a biologically sound basis for the immediate cultural improvement of the present generation of forest trees.

The objective of a sound silvicultural practice cannot, however, be confined to the present. A primary concern of the silviculturist is that natural reproduction should be abundant and that a favorable environment for its development should be provided. He should, certainly, also demonstrate some concern over its genetic quality. American silviculture is in urgent need of

criteria with a sound genetic basis that may at least insure perpetuation of the best of the wild types in the stands and forests of our several forest regions.

The silviculturist, in the practice of his trade or art, manipulates the environment chiefly by the use of axe or saw, and thus through the exigency of thinnings, improvement cuttings, etc., continuously exerts a direct and controlling influence on the genetic composition of the stand. Although we are in possession of little evidence that will provide a basis for a technically sound judgment, we may reasonably conclude that the early and uncontrolled exploitation of our native forests resulted in a profound and far-reaching disgenic influence. Not only were our forests combed and recombed for the most vigorous, healthiest, and best formed trees, but without adequate subsequent protection from logging fires, they were subjected also to successive burnings, which in some areas have all but eliminated the original native tree growth.

In the absence of specific genetic data based on progeny tests, we cannot as yet with any certainty make recommendations for the preservation or elimination of individual trees based on their phenotype. We can, however, make the reasonable assumption that diseased, poorly formed and otherwise phenotypically undesirable trees should be eliminated as early in the stand's history as possible. Fortunately such a procedure is acceptable under any cultural theory, since an increased yield and quality of the current rotation will be directly favored. To the credit of our silvicultural practice in this connection, we must also recognize that the probable disgenic effects of "high grading" practices, such as cutting to a diameter limit, have been legally outlawed in most states. This does not necessarily mean the elimination of such practices, but it does represent a promising step in the right direction.

Consideration has thus far been given to the value of genetic research into the characteristics of our forest trees as a means of enriching the quality of our silvical knowledge which may in turn be used immediately and with profit by the silviculturist. If the silvical data are expertly used, marked improvement in stand or forest quality and yield may be achieved; but it must be realized that individual tree quality has little chance for improvement beyond the best of the wild native genotypes present in the area treated. On a very large percentage of our forest lands such limited improvement will doubtless prove to be economically satisfactory for the present.

Locally, however—and this appears to be especially true in those areas of high human population in the East—the genetic quality of the residual stands may be so low that tree breeding programs must be relied upon to fulfill specific local needs. For such areas as these, and for those which have been completely denuded of their tree growth, planting is necessary. Under such conditions, and it is likely that such conditions will present themselves more frequently as time goes on, the special activities of the tree breeder must be relied upon to supply planting stock of genetically superior quality.

In general, the same genetic principles as those involved in agricultural crop improvement are utilized by the forest-tree breeder; but due to certain peculiarities of the material with which he works, procedures and techniques may be vastly different. The most important of these peculiarities is the flowering habit. Crops such as wheat and corn, for instance, may be relied upon to flower several weeks after the seed is sown. Most forest trees, on the other hand, require from two to eight years before the first flowers are produced. Furthermore, an added complication with trees is the fact that flower production in some species is often cyclic or erratic, flowers in abundance being produced only every two to four years. For this reason, chiefly, breeders facile in the handling of annual crops have sometimes been critical of the time factor in tree breeding.

Tree breeders, however, who must certainly be patient men, do not view this situation with the same alarm and foreboding for the following reasons:

(1) First, if the problem is viewed philosophically and quite independently of the time element, it is difficult to understand why an improved race of trees (which may have taken twenty years to produce) is of less intrinsic value than a comparable improvement in rhubarb which may have taken five years.

(2) Secondly, by special seedling treatment many species may be induced to flower from two to four years in advance of the time for them to reach normal flower-producing maturity.

(3) Finally, in contrast to wheat or corn breeding, an improvement program need not and preferably should not be based on what would certainly be a time-consuming inbred pure-line method.

This is a point frequently overlooked or misunderstood by the grain or vegetable breeder, who thinks of yield in terms of a harvest which involves each and every plant on the acre. The history of a forest stand, however, which is grown to saw-log

size reveals that during the 60- to 100-year period involved, as much as 90 per cent of the original stand may be removed by natural or artificial thinnings. Thus in a white pine plantation, for instance, with an original spacing of 6 x 6 feet, about 1200 plants per acre will be set out; but only about 120 of these will be allowed to survive until the final harvest. Certainly, under such conditions, a high degree of genetic purity is unnecessary.

As the first step in a tree improvement program, exploratory investigations are required for the purpose of providing information on the nature and extent of the wild variability throughout the range of the species or genus under consideration. The conclusive genetic basis of this variability cannot, of course, be determined by phenotypic selection; but if the original selections are based on apparent health, vigor, stem form, and similar characters, as compared with associated individuals in the wild stands, the chances are better that the most desirable gene combinations within each geographic area will be identified.

No satisfactory test has yet been devised as a substitute for the progeny test as a means of assessing the genetic quality of individual trees, and there probably never will be. This does not mean, however, that the breeding work must be suspended until the progeny tests are completed. Cross combinations involving phenotypically superior individuals of the same or related species from the same geographic area may be undertaken, and the tests of such hybrid progenies run concurrently with the progeny tests.

For a number of years such a method of procedure has been successfully operated in Sweden. Teams of trained specialists have surveyed the millions of hectares of Sweden's forests and classified native stands as "plus", "normal", or "minus". In cooperation with the national and state forestry agencies, as well as private landowners, seed collections within local areas have been made as much as possible only from the phenotypically superior "plus" stands. Plantations of plants derived from such stands have been made as a part of the normal planting program, and large-scale progeny tests are thus in progress at small extra cost. Even if the tests from the genetic point of view yield unsatisfactory results, there will be no marked loss in production, since the yield will undoubtedly compare favorably with the average of the wild type present in the area.

Similar methods of testing hybrid progenies have been used. In such cases only a comparatively small number of hybrid trees are planted in mixture with wild native strains. These are reg-

ularly distributed throughout the plantation area, and careful records are kept. If the hybrids are indeed found to be superior to the wild type, the wild type trees can serve as trainers. If, on the other hand, the hybrids are unable to compete or are in other ways undesirable, they will be eliminated by natural or artificial means; and no loss in production for the area concerned will be involved.

On the basis of the performance demonstrated by many inter- and intraspecific F_1 hybrid progenies in Europe and this country, such progenies, derived from crosses of carefully selected parent trees, offer one of the most promising means for the production of superior planting stock for use in reforestation programs.

Such progenies frequently demonstrate marked hybrid vigor, with growth in height and diameter far in excess of those demonstrated by the best of the wild type. This is a point of considerable importance in forestry, where the elapsed time between planting and final harvest may be more than a human lifetime. If this time can be shortened by one-third or even more, the recommendations of foresters may be given more than passing lip service by the private landowner.

But in addition to an increased growth rate, such F_1 hybrids may combine the best characters of the parental types as well. Some of the best examples of such hybrids are those resulting from selected parents of the European larch and Japanese larch. Hybrids of this cross demonstrate rapid growth in combination with the good stem form of the European larch and resistance to larch canker contributed by the Japanese larch. Similar results have been obtained from crosses involving our native trembling aspen and the European aspen. Hybrid vigor is here combined with good stem form and branching habit and almost complete immunity to *Melampsora* rust which, in many parts of Europe, is a limiting factor in the growing of the native aspen.

In the case of certain cross combinations of proved value, it may be desirable to insure a continuous and abundant source of hybrid seed for large-scale plantation establishment. For this purpose seed "orchards" or seed "plantations" have been undertaken on a large scale in various European countries. By this method, the desired parents are vegetatively propagated and then planted in alternate rows in the orchard and allowed to interpollinate at will. Early and regular flower production is stimulated by root-pruning and strangulation. By top-working, the crowns may be kept low and broad to facilitate seed collection.

The science of forest-tree genetics and its application to forestry as an aid in the solution of silvicultural problems is still a new and incompletely explored field. Evidence is, however, sufficient to justify the conclusion that if our silviculture is to have a sound biological basis, and thus insure for our own and future generations the maximum conversion of solar energy, we cannot safely continue to ignore the existence of intraspecific variability in forest trees and the manner in which it is inherited.

Silvical facts which accrue from the study of phenotypes derived from *known* genotypes in a *known* environment will provide the silviculturist with a means of exerting a wise and predictable influence on the current growth and development of the stand. As information on inheritance in trees accumulates, the silviculturist may even be able to exert a direct and controlling influence over the genetic quality of the reproduction. Finally, under intensive management practices, we may safely predict that through the utilization of forest-tree genetic facts, high yielding and otherwise desirable hybrids may be produced and propagated at will.

NON-BIOLOGICAL PHOTOSYNTHESIS

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This paper is concerned with research under way in the Department of Chemistry of the Massachusetts Institute of Technology, on the design of a non-biological photosynthetic process in which water is decomposed by sunlight into the component hydrogen and oxygen, not by the sunlight absorbed by water, but by the sunlight absorbed by inorganic material that has been added to the water. It is desirable first to review briefly some pertinent aspects of the natural process, and the work which led to recognition of the new process as a means of converting solar into chemical energy.

Photosynthesis is usually thought of as the process by which living plants absorb sunlight and thereby convert carbon dioxide and water into oxygen and compounds of carbon. The compounds of carbon produced by the reaction include carbohydrates (such as sucrose) which store up part of the energy of the sunlight in the form of chemical energy. This energy can be released when desired by burning the sugar to produce heat and give back carbon dioxide and water. The growing of sugar cane is, in fact, one of the most efficient natural ways to convert solar into chemical energy, as has been pointed out in an earlier paper of this series by Dr. Daniels.

The natural process is brought about, as is well known, not by the sunlight absorbed by the carbon dioxide and water which produce the sugar, but by the sunlight absorbed by the chlorophyll in the system. Two aspects of the natural process have been of particular interest. One is the question of how the carbon in the carbon dioxide is reduced to the form in which it is found in sugar; the other is the question of how the oxygen in water is oxidized to oxygen gas.

The problem of learning how the carbon is reduced is difficult to attack experimentally because no sure way has been found to reduce carbon dioxide photochemically in water solution outside of a living organism.[1]

The other problem of learning how the oxygen in liquid water

is oxidized photochemically to oxygen gas is easier to attack experimentally because the reaction occurs in some simple inorganic systems. Our approach to this problem[2] has shown that bivalent oxygen in water solution is oxidized photochemically to oxygen gas only if the oxygen is attached directly to the particle absorbing the light and to other particles so that two electrons are transferred away from the oxygen before it leaves the photochemically reactive cluster; that is, the reaction appears to proceed without the formation of peroxide as an intermediate outside of the photosensitive cluster.[3]

The process is summarized by the chemical equations given in Table 1. The metal ions are those of the metal cerium in oxidation states three and four, but there is no obvious reason why the ions of any other metal which absorbs the same kind of light in two different states of oxidation could not be used.

TABLE 1

Non-Biological Photosynthetic Process

(1)	$2Ce^{+4} + H_2O + \text{Light} = 2Ce^{+3} + \frac{1}{2}\,O_2 + 2H^+$	36%
(2)	$2Ce^{+3} + 2H_2O + \text{Light} = 2Ce^{+4} + H_2 + 2OH^-$	0.1%
(3)	${}_1Ce^{+4} + {}_2Ce^{+3} + \text{Light} = {}_1Ce^{+3} + {}_2Ce^{+4}$	
(4)	$2H^+ + 2OH^- = 2H_2O$	
(5)	$2Ce^{+4} + 2Ce^{+3} + H_2O + \text{Light} = 2Ce^{+3} + 2Ce^{+4} + H_2 + \frac{1}{2}\,O_2$	

Reaction (1) of this table was studied[2] to learn something about the way oxygen in water is photochemically oxidized to oxygen gas. In this reaction the ceric ions absorb the light and thereby oxidize the water to oxygen.

Reaction (2) was discovered in our search for an explanation of the inhibiting effect of Ce^{+3} ions upon reaction (1). In reaction (2), Ce^{+3} ions absorb light and are thereby oxidized to Ce^{+4} ions. Thus, the loss of Ce^{+4} ions brought about by the reaction (1) is partly offset by the photochemical formation of these ions by reaction (2) when Ce^{+3} ions are present.

The production of Ce^{+4} ions by reaction (2) was proved by observing that the irradiated portion of a solution of cerous perchlorate containing initially no ceric ions turned yellow when sulfuric acid was added to it because of the formation of the yellow ceric sulfate complex, but that this did not occur in the portion of the solution that had not been irradiated.[2]

We have very recently proved the production of hydrogen gas by reaction (2) by observing that the gas produced by the reaction reduces hot black cupric oxide to metallic copper. Since this material has not been published, the experiment will be described briefly. The work was carried out with an aqueous solution containing 0.01 mole cerous perchlorate (G. F. Smith Co. hydrated reagent grade) and one mole perchloric acid (Baker's C. P. 70 - 72 per cent perchloric acid) per liter; but the solution did not contain any ceric cerium at the beginning of the period of irradiation. The apparatus employed to irradiate the solution has been described.[4] The reaction vessel was made of water-white fused quartz; it was cylindrical in shape and 28 mm. i.d. The solution was stirred continuously, while being irradiated, with a one-millimeter thick rectangular plate of water-white fused quartz that was rotated slowly within the reaction vessel and passed within one mm. of the wall of the vessel. Before the solution was irradiated, it was freed of all gases by reducing the pressure above the solution at 25°C to its vapor pressure while the solution was stirred to avoid bumping. The evacuation was continued until about one ml. of water had evaporated from the solution, whereupon the system was sealed off from the pumps.

The sealed system contained a stopcock next to the reaction vessel, a trap for freezing out the water vapor with liquid nitrogen, a horizontal tube containing a very thin layer of finely powdered dry black cupric oxide, and a Macleod gauge all made of pyrex glass. The stopcock between the reaction vessel and the cold trap was closed while the solution was being irradiated. Care was taken to insure that the closed system was gas-tight.

The solution was irradiated at 25°C for a period of nine hours with 10^{18} quanta per second of ultraviolet monochromatic light of wavelength 254 mu. incident upon it on all sides, and this light was completely absorbed by the solution. After the solution had been irradiated, the cold trap was cooled to the temperature of liquid nitrogen and the gas produced by photolysis was allowed to pass through the trap to the glass tube containing the cupric oxide which was then gently warmed with a gas flame whereupon a mirror of metallic copper was produced in the glass tube. Blank experiments were carried out without irradiation of the solution, but these gave no metallic copper, thereby proving that the gas produced by the photolysis was responsible for the production of the metallic mirror. The only gas that could be produced by the photolysis and would produce the mirror of metallic copper from cupric oxide under these conditions is hydrogen.

Reaction (3) of Table 1 has been found to take place thermally by employing radioactive cerium as a reactant in an oxidation state of either $+^3$ or $+^4$, and observing that it soon takes on the valence of the non-radioactive cerium in the solution.[5] Reaction (2), it will be recalled, accounted for only part of the inhibiting effect of Ce^{+3} ions upon reaction (1); the remaining part of this effect can be accounted for by a reaction like (3) in which Ce^{+3} ions deactivate Ce^{+4} ions that have absorbed light. In like manner it is very likely that Ce^{+4} ions will be found to inhibit reaction (2) by deactivating Ce^{+3} ions that have absorbed light.

Reaction (4) represents the neutralization of an acid by a base and is well known.

Reaction (5) summarizes the new photosynthetic process. The equation is the sum of the other reactions, and shows how liquid water may be decomposed by light into hydrogen and oxygen, thereby converting part of the energy of the light into chemical energy. The ceric and cerous ions have been left in this reaction to show that they play the role of the light-absorbing species in much the same way that chlorophyll plays this role in the natural process. The only substance consumed by the reaction is water.

The hydrogen and oxygen gases produced by the reaction store up solar energy that has been converted into chemical energy. This energy can be released by burning the gases; and it is worth noting that since the temperature attained in the hydrogen-oxygen flame is every high, the maximum efficiency with which the heat can be utilized is also high.

The amount of energy produced by burning two moles of hydrogen with one mole of oxygen is very nearly the same (over 100 kilogram-calories) as the amount of energy produced by burning one-twelfth mole of sucrose monohydrate (one CH_2O unit) with one mole of oxygen; and both these quantities of material are produced by the photochemical liberation of one mole of oxygen, in the first case by the non-biological process and in the second case by the natural photosynthetic process.

The highest quantum efficiencies that have been observed thus far for reactions (1) and (2) in Table 1 are shown. The efficiency is seen to be about 36 per cent in the case of reaction (1), and about 0.1 per cent in the case of reaction (2), but no attempt has thus far been made to increase these efficiencies which are based on the change in the concentration of ceric ions and are minimum values for the production of the gases. These efficiencies would, in fact, be zero when reactions (1) and (2) proceeded at the same

rate even when there was nearly complete conversion of solar into chemical energy. The efficiency of this conversion of energy is directly proportional to the quantum yield of the production of the gases hydrogen and oxygen by reaction (5), not to the change in the concentration of either ceric or cerous ions. Reaction (5) will be competing, of course, with reaction (3). Our results indicate[2] that the photosynthetic process represented by reaction (5) will be most efficient when the ratio Ce^{+3} to Ce^{+4} ions in the solution is high and when the acid concentration is less than one mole per liter.

It should be noted that the photo-oxidation of water by ceric ions in reaction (1) does not proceed against the gradient of chemical potential or of total energy; that is, it does not convert any light energy into chemical energy. Moreover, it can be made to take place at a measurable rate without the absorption of light simply by raising the temperature above 35°C.[6] Reaction (2), however, does proceed against the gradient of chemical potential as shown by the fact that the normal potential of the cerous-ceric system is more positive than that of the hydrogen electrode. It also proceeds against the gradient of total energy, that is, with the conversion of part of the light energy into chemical energy. Moreover, the gain in total energy obtained by reaction (2) more than offsets the loss in total energy by reaction (1); so the net result of the two reactions is a gain in total energy at the expense of the light energy absorbed by the system.

The systems in which these reactions have been studied are acid solutions of the positive ions of the metal and of the negative perchlorate ion. The negative perchlorate ion has been employed because it does not absorb visible or ultraviolet light; it has the smallest tendency of all negative ions in water to associate itself with other ions or molecules, and it is quite inert chemically in dilute solution. It is, in fact, the most inert, transparent, isolationist that exists in dilute water solution.[6]

In systems of the type being discussed, light is absorbed by both valence states of the metal ion and is believed to produce an electron transfer between the ion and its closest neighbor. The photochemical effects of a few of these transfers were discussed[7] in 1942 by Rabinowitch. At the time the article was written, there was no experimental work that suggested the possibility that the absorption of light by a suitable inorganic system containing the ions of only one metal in two different states of oxidation could be used to decompose water into its elements.

Rabinowitch recognized, however, that the subject of the

photochemical effects caused by the electron transfer bands of anions and cations in solution certainly deserved a more extensive study. He also noted that the photo-reduction of water by ferrous ions proceeds against the gradient of chemical potential, as shown by the fact that the normal potential of the ferro-ferri system is more positive than that of the hydrogen electrode, and also proceeds against the gradient of total energy; that is, with the conversion of part of the light energy into chemical energy. He further noted that there was no obvious reason why ferric salt solutions illuminated by ultraviolet light should not liberate oxygen, but he did not state the possibility that if the photochemical oxidation and reduction of ferrous and ferric ions or of the ions of any other metal in two different states of oxidation could be made to take place in the same solution, a situation would exist where the amount of metal in each state of oxidation would remain constant while light absorbed by the metal ions photochemically decomposed water into its elements.

In carrying out the work on these reactions, several conventional procedures have been cast aside. In the first place, the experiments have not been restricted to the use of sunlight or even to the range of wavelengths in sunlight as it reaches the earth's crust. Advantage has been taken of the fact that the kinetics of most photochemical reactions of this kind do not depend strongly upon the wavelength of the absorbed light as long as this light is in the near ultraviolet part of the spectrum, of wavelength longer than 2000 A. At the present time most of the work is being carried out with monochromatic ultraviolet light of wavelength 2537 A. This light is obtained very pure, and up to very high intensities which can be easily controlled. In the second place, all measurements have been made on a quantum-yield basis. This has made it possible to compare our results on a quantitative basis which makes them much easier to interpret and eliminates many treacherous pitfalls that may otherwise lead to erroneous conclusions, especially when monochromatic light is not employed.[8]

References and Comments

[1] The latest claim to the discovery of a way to reduce carbon dioxide photochemically outside of a living organism has been disproved by Linstead, R. P., Braude, E. A. and Timmons, C. J., *Nature 166*, 557 (1950).

[2] Heidt, L. J. and Smith, M. E., *J. Am. Chem. Soc. 70*, 2476 (1948).

[3] EVANS, M. G. and URI, N., *Nature 166,* 602 (1950) and others to whom they refer believe that the reaction proceeds mainly by way of the production of free hydroxyl radicals following the absorption of light by particles containing one ceric ion. They find it necessary, however, to attribute to impurities the part of our results that does not agree with their hypothesis.

[4] HEIDT, L. J., *Science 90,* 473 (1939).

[5] LINNENBOM, V. J. and WAHL, A. C., *J. Am. Chem. Soc. 71,* 2589 (1949). [See also GRYDER, J. W. and DODSON, R. W., *J. Am. Chem. Soc. 71,* 1895 (1949) and DWYER, F. P., GYARFAS, E. C. and MELLOR, D. P., *Nature 166,* 746 (1950).]

[6] The nature of ceric ions in the solution in which reaction (1) was studied is given in Table 2. The highly-charged Ce^{+4} ions are completely (over 90 per cent) hydrolyzed to $Ce\,OH^{+3}$ and other products even when the solution is over one-molar in perchloric acid. Ceric dimers, trimers, etc., are produced by splitting out water from two hydroxyl groups attached to different ceric ions in the manner shown by the equation given in Table 2.

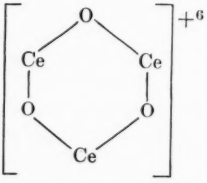
TABLE 2

The Nature of Ceric Ions in Perchloric Acid

Monomers: Ce^{+4}, $CeOH^{+3}$, $Ce(OH)_2^{+2}$, etc.

Dimers: $Ce\text{-}O\text{-}Ce^{+6}$, $Ce\text{-}O\text{-}CeOH^{+5}$, $HOCe\text{-}O\text{-}CeOH^{+4}$, etc.

Trimers: $Ce\text{-}O\text{-}Ce\text{-}O\text{-}Ce^{+8}$, $Ce\text{-}O\text{-}Ce\text{-}O\text{-}CeOH^{+7}$, $HO\text{-}Ce\text{-}O\text{-}Ce\text{-}O\text{-}CeOH^{+6}$ etc., and rings like



Reaction: $Ce\text{-}OH^{+3} + HO\text{-}Ce^{+3} = Ce\text{-}O\text{-}Ce^{+6} + H_2O$

The equilibrium concentration constant of the reaction for the combination of like monomers at an ionic strength of about unity was found[2] to be 50 ± 10, and for the combination of unlike monomers, it was found to be 100 ± 10. It will be noted that the water of hydration has been left out of the formulas of the ions.

The value of the equilibrium constant is given in terms of volume concentrations and was evaluated from the change in the quantum yield of reaction (1) brought about by changing the concentration of the ceric perchlorate. The existence of reactions like the one given in Table 2 has been

recognized for a long time, but the equilibrium constant of a particular reaction of this kind had not been evaluated previously. Experiments are now in progress to evaluate the thermodynamic constants of equilibria of this kind.

The fraction of the ceric cerium in the form of dimers, trimers, etc., has been found to increase when the total concentration of the ceric cerium in the solution is increased and when the acidity of the solution is decreased. The fraction of the ceric cerium in these forms is 0.01, 0.09, 0.39 and 0.45 when its formal concentration is 0.0001, 0.001, 0.01 and 0.015 molar respectively in one molar perchloric acid. The distribution of the dimers among the various forms is given in Table V of reference 2.

These reactions are in accord with all of the experimental facts regarding not only the photochemical oxidation of water by ceric ions, but also the e.m.f. measurements of M. S. Sherrill, C. B. King and R. C. Spooner as has been shown in reference 2, and the thermal oxidation of water by ceric ions as has been shown by D. Kolp and H. C. Thomas, *J. Am. Chem. Soc. 71,* 3047 (1949). The electromotive force measurements were made of a voltaic cell consisting of a bright platinum electrode dipping into a solution of cerous and ceric perchlorates and perchloric acid, and a hydrogen electrode dipping into a perchloric acid solution of the same strength as around the other electrode.

[7] RABINOWITCH, E., *Rev. Modern Phys. 14,* 112 (1942).

[8] Acknowledgment is made of the financial assistance of the Godfrey L. Cabot Solar Energy Fund of the Massachusetts Institute of Technology for the photochemical work conducted on the cerium system since September, 1949.

PART 2

SUN-EARTH RELATIONSHIPS

DONALD H. MENZEL
Chairman

THE ANALYSIS OF THE SOLAR AND TERRESTRIAL ATMOSPHERES

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It may well turn out that the most important service of the sun to man has been to provide him with a typical star strategically placed close enough at hand to be studied by astronomers in fairly minute detail. Many other stars in the sky are infinitely more spectacular than our sun, and if we could examine them from nearby, we should undoubtedly learn a great deal more of the operation of the laws of nature than we have to date. There is some point, however, in being thankful for what we have, and I am sure that even the most ardent observers would not wish to substitute for the sun a more interesting star with perhaps explosive tendencies.

Despite its rather ordinary qualities as a star the sun does influence the earth in a great many ways and solar research has important practical applications, even though many of them may still be tentative and potential. In fact, it is very difficult to escape from the everyday applications of solar research. If a group of practical-minded men were to assume control of all of our solar observatories and decide that henceforth only those researches were to be carried out that had a foreseeable human impact, it is doubtful that existing research programs would be appreciably changed. The point is, of course, if we are ever to succeed in understanding fully the effects of solar radiation on the ionosphere and radio communications, on the temperature balance of the earth's atmosphere and the weather, and on the biology of plants and animals, we must strive for complete understanding of the solar operation. It will not be enough to study by themselves isolated phases of the solar problem such as the corona, or prominences, or sunspots, or flares, or the various X-ray, optical and radio regions of the radiation spectrum.

The utility of solar research is evidenced by the support it receives from government agencies. Both the Navy and the Air Force conduct solar studies in their own laboratories and support other investigations at various universities throughout the country. The Bureau of Standards, through its Central Radio Propagation Laboratory, contracts for daily reports of solar activity from solar observatories, and employs the data for forecasts of

terrestrial radio communication conditions, with which solar disturbances are intimately related. Two new solar observatories with large and powerful equipment are now being constructed under service sponsorship, the first by Harvard University and the Air Force at Sacramento Peak in New Mexico, and the second by the Office of Naval Research and the High-Altitude Observatory of Harvard and Colorado Universities at Chalk Mountain near Climax, Colorado.

The human impact of modern solar research can best be illustrated by describing a number of investigations currently in progress at the McMath-Hulbert Observatory of the University of Michigan. They form a portion of a long-range program of analysis of the solar and terrestrial atmospheres being pursued by a team of investigators under the direction of Dr. Robert R. McMath. Although only the highlights of the solar research program of a single solar observatory are here presented, it should be emphasized that the efforts of a great many solar observatories will be required if the solar problem is ever to be solved satisfactorily. The sun operates on a 24-hour basis, not alone when the skies are clear. Even more importantly each observatory approaches solar research from a different point of view, and usually also with different types of instrumentation. For example, a great many solar phenomena are visible in monochromatic light only and elaborate equipment must be devised to form monochromatic solar images. At the Mount Wilson and McMath-Hulbert Observatories, tower telescopes and spectroheliographs are used for this purpose, whereas at the Harvard stations on Sacramento Peak and Chalk Mountain, coronagraphs and polarizing filters will be employed. Both methods have their advantages and drawbacks.

Observations at the McMath-Hulbert Observatory are made in the three buildings shown in Fig. 1. The small dome in the foreground houses a 24-inch reflecting telescope to which is attached a Perkin-Elmer infra-red spectrometer. This device is used to record the sun's infra-red radiation in the wave length region from 3 to 20 microns. The second building contains a 50-foot solar telescope that feeds sunlight to a spectroheliograph below ground. This instrument makes automatic motion picture recordings of the activity of solar gases and has been in operation since 1936. The 50-foot tower also contains a second solar telescope and spectroheliograph that is used to record radial velocities, or motions along the line of sight, of prominence and disk activity. The combination of records from the two instruments gives the

three-dimensional motion of the solar gases. The 70-foot McGregor tower in the background also contains two separate telescopes and spectrographs. The first optical system uses lenses to form a solar image as large as 11 inches in diameter. The image may be recorded directly by motion-picture photography or it may be fed to a Littrow spectrograph for photography of the spectrum with a dispersion of 2A per mm. The second optical system is especially designed for analysis of infra-red radiation and is constructed almost entirely of mirrors. The energy detector is a lead sulfide photoconductive cell and the instrument as a whole delivers direct-intensity tracings of the solar spectrum at very high dispersion. The region of sensitivity is between 5,000 and 36,000 angstroms and the maximum resolving power at 16,000 angstroms is about 50,000. Recently a third spectrograph has been added to the McGregor tower, which makes use of a so-called echelle grating, designed by G. R. Harrison and constructed by Bausch and Lomb. The echelle grating makes possible the photography of about 3,000 angstroms of the solar spectrum on

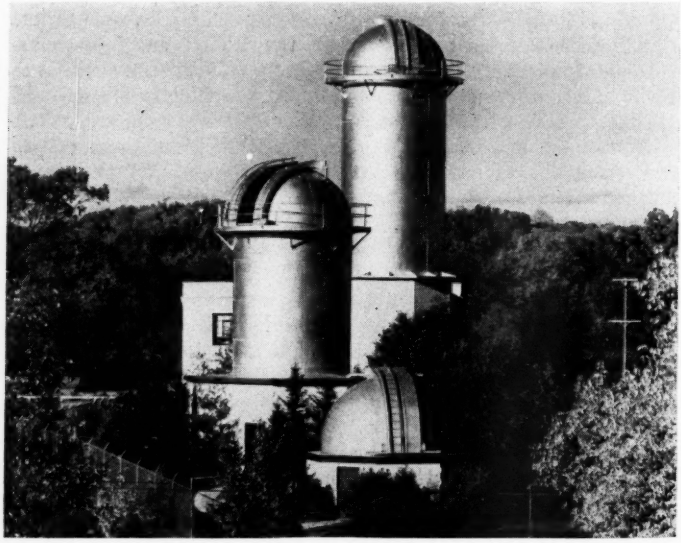


FIG. 1. The McMath-Hulbert Observatory

a single plate, with a dispersion of several millimeters per angstrom and with a resolving power of several hundred thousand. Finally, a duplicate of the high-dispersion infra-red spectrometer has been constructed by the McMath-Hulbert Observatory and installed at the Snow telescope of the Mount Wilson Observatory under a cooperative arrangement.

The research programs of the McMath-Hulbert Observatory may be grouped conveniently under three major headings, namely, (1) the structure of the solar atmosphere, (2) studies of flares, prominences, and associated terrestrial activity, and (3) studies of infra-red radiation. One of the basic problems in solar physics is the determination of an accurate model of the solar atmosphere, that is, a determination of the variation of temperature, pressure, and absorption coefficient with depth. The observational data required for this purpose consist of measurements of solar limb darkening at all accessible wave lengths in the spectrum together with a precise determination of the energy distribution with wave length of the radiation from the center of the sun's disk. If the sun had a sharply defined radiating surface, its surface brightness would be constant all over the disk. Actually, of course, the sun does not have a sharp boundary; the intensity and temperature of the surface gases increase with depth and the extent to which one can see into the sun's atmosphere in the light of a particular wave length is a function of the temperature and pressure gradients as well as of the absorption coefficient of the gases. In general, the radiation emerging from the limb of the sun comes from higher levels in the atmosphere than does the radiation from the center of the disk. Consequently, the limb appears darker and the rate at which the degree of darkening diminishes towards longer wave lengths is determined by the dependence of the absorption coefficient on wave length.

Measures of solar limb darkening have been carried out by Abbot and others and tentative model atmospheres calculated from them. Recently Dr. Pierce and his co-workers at the McMath-Hulbert Observatory have extended the measurements to relatively long wave lengths and these new observations are being analyzed by Pierce and Aller with the aim of deriving a newer, more accurate model solar atmosphere. As a necessary corollary to this work the spectral energy distribution of the radiation from the sun's disk is being measured both in the visible and in the infra-red. When the model atmosphere is finally derived, it may be used to calculate intensities of various types of absorption

lines in the spectrum to compare with observation. The results will also be valuable in investigations of turbulence in the solar atmosphere as well as in the theoretical calculation of radio emission from the sun. It should be remarked that analysis of limb-darkening measurements yields only the structure of the lower portion of the sun's atmosphere, the region that is more or less opaque to optical radiation and in which the Fraunhofer absorption lines are produced. The structures of the higher chromosphere and corona can best be deduced from observations made at times of total eclipse and from observations of radio radiation.

The second phase of the program is concerned with the study of transient phenomena in the sun's atmosphere, i.e., the sunspots, prominences, flares, dark filaments, etc. This phase of the work was begun by Dr. McMath in the early 1930's when he first applied the technique of motion-picture photography to the problem and is now under the immediate supervision of Dr. Helen W. Dodson. Dr. McMath's first photographs were taken in the usual two-dimensional fashion. From them one could measure the projections of the prominence motions on the plane of the sky. Later he devised the so-called radial-velocity spectroheliograph which records the motions of gases along the line of sight and therefore makes possible the measurement of three-dimensional space motions. From the motion-picture records come not only the space trajectories of prominences, but also their brightnesses with reference to the intensity at the center of the sun's disk.

The forces that act on solar prominences are both gigantic and complicated, as is evidenced by the often very rapid accelerations of the massive gas clouds and by the usually intricate paths they follow (see Fig. 2). By far the great majority of prominence material appears to be in motion downward toward the surface of the sun, often with accelerations that exceed that of solar gravity. Probably additional forces due to radiation pressure and to electric and magnetic fields are also present. The exact role they play will eventually be deduced from detailed analyses of the motion-picture records.

One class of prominences, the so-called surge type, does appear to have a relatively simple motion. The surges are characterized by high speed and short duration. The material surges out of the chromosphere on what appears to be a straight-line path and then returns along the same trajectory. Surge velocities as high as 1000 km/sec have been observed. The behavior of a typical surge is illustrated in Fig. 3. Fig. 4 shows the measured trajec-

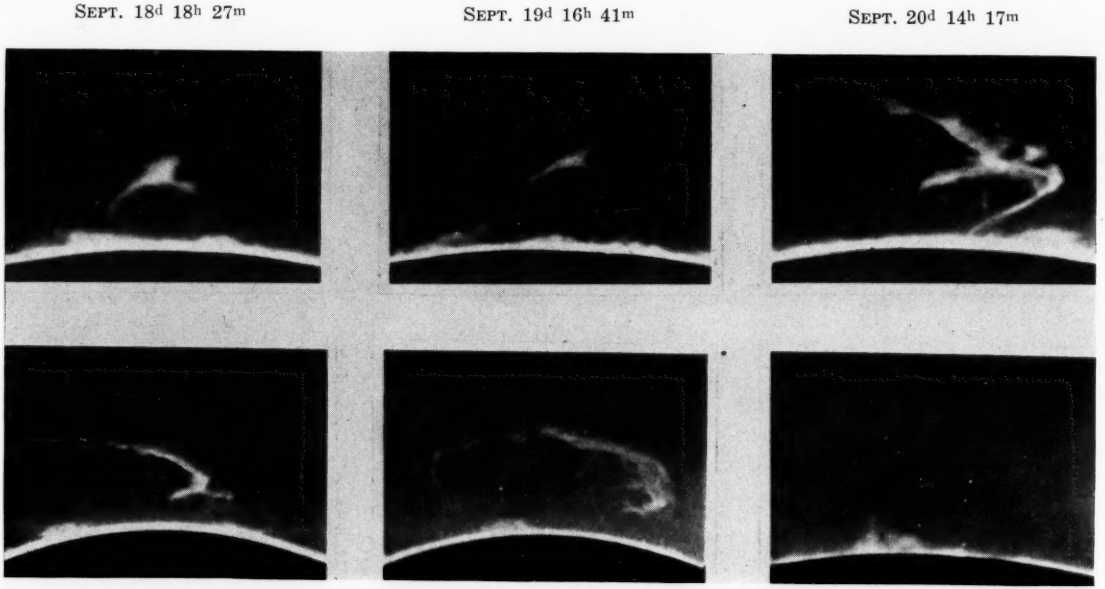


FIG. 2. Prominence of September 18-21, 1946.

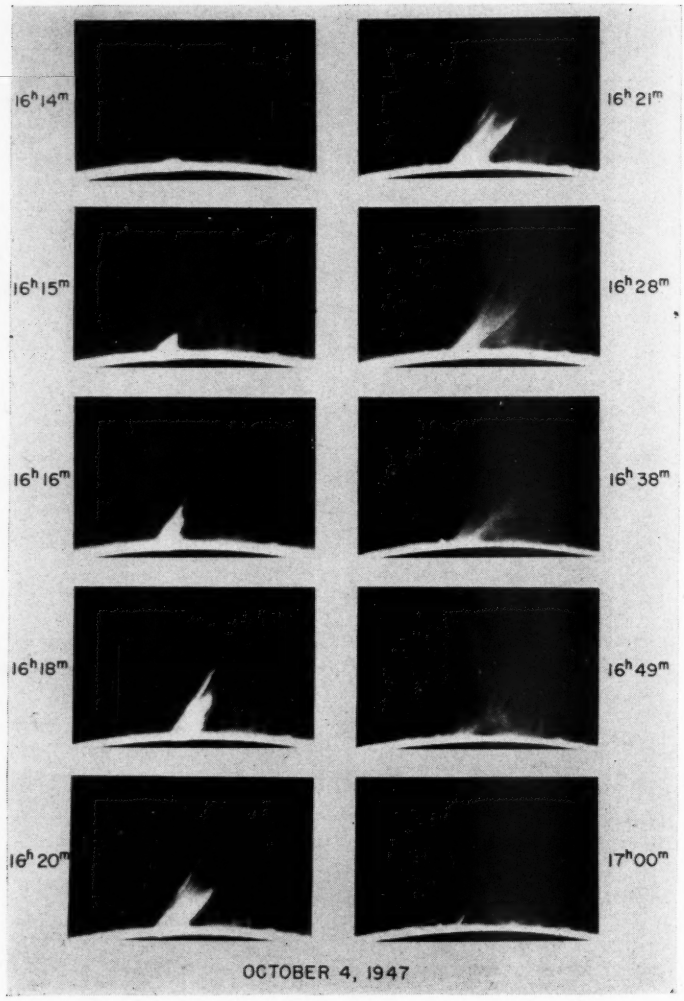


FIG. 3. Surge-Type Prominence, October 4, 1947.

tories of this and other representative surges studied by Dr. Dodson and Miss E. Ruth Hedeman. Actually, the plotted points do not represent the complete trajectories, only the height of the top of each surge as a function of time. The solid curve in each case is the calculated variation of height with time on the assumption that the only radial force on the gas is that of solar gravity. It can be seen that the calculated curves fit the observations very well. The repeating surge of May 16, 1947, is especially interesting. This object recurred periodically along the same path at intervals of ten or fifteen minutes. Apparently the gas received a succession of upward impulses of unknown origin. At all times, however, the vertical component of the motion appeared to be governed by solar gravity.

The prominences are spectacular and the problems they pose are intriguing, but no more so than the activity that takes place on the disk of the sun. Fig. 5 shows a representative sample of

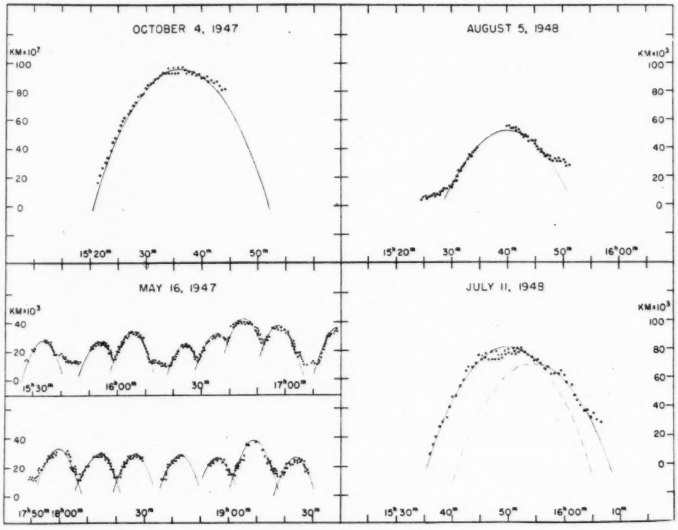


FIG. 4. Height-Time Relationships for Representative Surges.

The dots and crosses represent measurements for the top of each surge, while the solid curves are the calculated trajectories due to solar gravity.

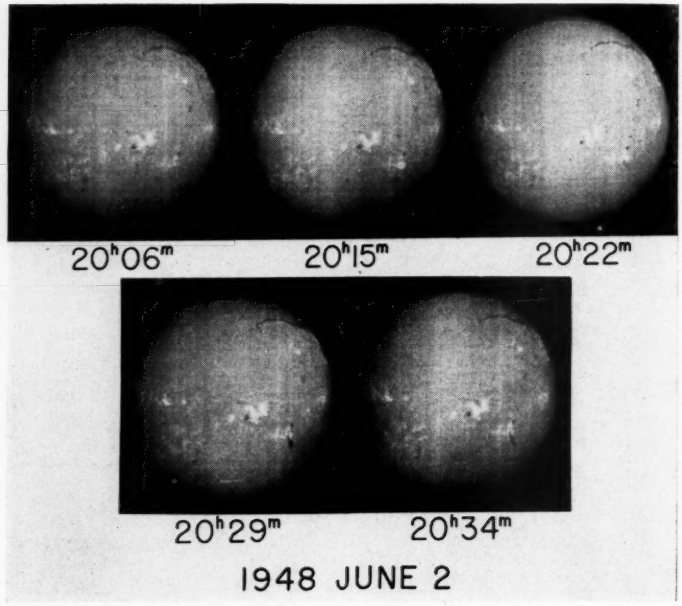


FIG. 5. The Solar Disk on June 2, 1948.

Note the small region near the right edge of the disk that brightens at 20^h15^m, followed by the ejection of a dark cloud beginning at 20^h22^m.

disk activity, photographed in hydrogen light. There are several groups of sunspots surrounded by bright areas which are called plages. At the upper right appears a long dark filament which is a prominence seen dark in projection across the bright disk. Notice the small sunspot near the right edge of the disk. At 20^h15^m a small area below the spot brightens; 7 minutes later a high-speed cloud of gas is ejected from the region of the flare. The behavior of dark filaments frequently borders on the mysterious. Fig. 6 illustrates the mysterious case of a vanishing filament that returned. The filament is first shown as it appeared on July 15, 1948, and again on August 11 after one complete rotation of the sun. Twenty-eight days later, after the sun had completed a second rotation, the filament was still present on

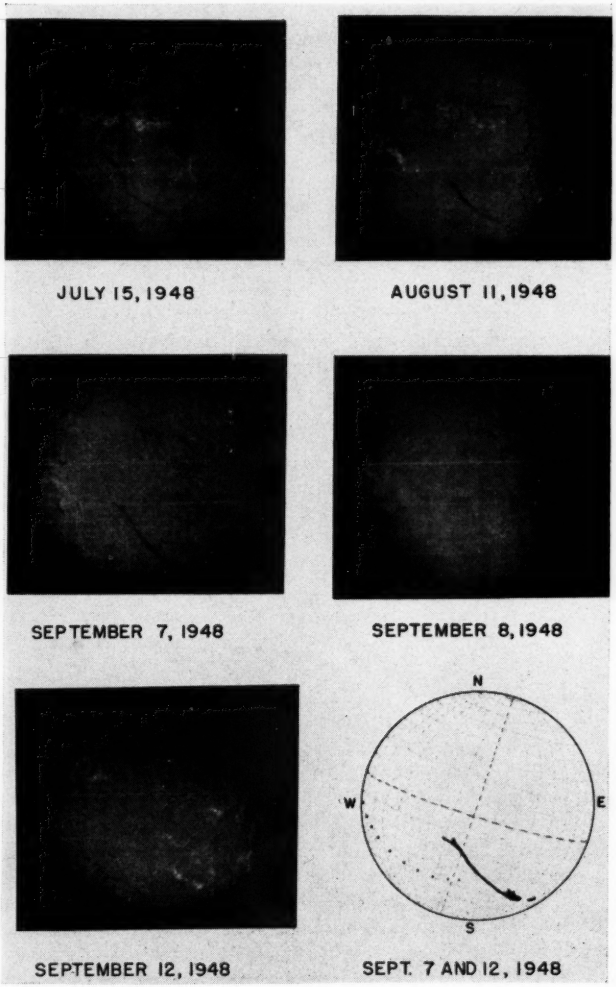


FIG. 6. Disappearing Filament.

Note the complete absence of the filament on September 8, 1948, and its reappearance on September 12, 1948. The map at the lower right shows the position of the filament on September 7 and its predicted position on the rotating sun for September 12.

September 7, but on the following day, September 8, it vanished. Four days later, however, it reappeared over exactly the same region of the disk and as far as can be judged with exactly the same shape.

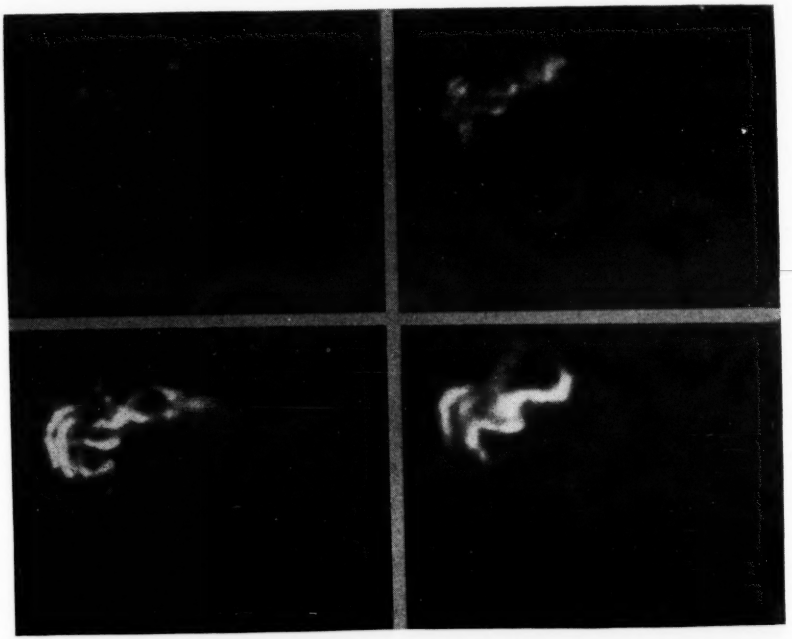
Fig. 6 also shows that several unusually bright areas appeared on the solar disk on July 15, August 11, and September 12, 1948. These are the so-called solar flares that seem to be so intimately related to ionospheric disturbances, magnetic storms, and subsequent interference with radio communications. The appearance of a typical bright flare is shown in Fig. 7. They occur in the neighborhood of sunspots and attain a brightness several times that of the surrounding disk in the space of a few minutes. The decline from maximum brightness usually proceeds much more slowly and after the event is over the surface of the sun looks very much as it did before the eruption.

It had been known for many years that solar activity in the flares and in the corona was in some way responsible for sudden ionospheric disturbances, or S.I.D.'s, for magnetic storms, and for interruptions to short-wave radio communications. Government interest during the last war provided the impetus for detailed study of the relationship between solar activity and radio communications. During the war the joint chiefs of staff sponsored a forecasting service at the Department of Terrestrial Magnetism. Each day reports of solar activity were sent to Washington from several cooperating solar observatories. Data on sunspots were supplied by the Mount Wilson Observatory and the Naval Observatory in Washington, on the corona by Harvard's High-Altitude Observatory at Climax, and on flare activity by the McMath-Hulbert Observatory. On the basis of these reports D.T.M. prepared for the armed forces regular forecasts of radio communication conditions. This cooperative program has continued in peacetime under the sponsorship of the Bureau of Standards where the forecasts are prepared at the Central Radio Propagation Laboratory by A. H. Shapley and his associates. The forecasts are pretty good, but unfortunately it has not yet been possible to establish a precise correlation between solar activity and ionospheric disturbances.

Dr. McMath, Dr. Dodson, and Miss Hedeman have been studying the flares and their relationships to ionospheric disturbances. They find that whenever the flares are very bright, about three times as intense as the background, S.I.D.'s take place regardless of the location of the flare on the solar disk or of the area of the disturbance. The brighter flares therefore present no particular

19h 50m

20h 02m



20h 06m

FIG. 7. Solar Flare, May 10, 1949

20h 22m

problem; it is the fainter ones that are puzzling. Two flares that were observed on November 1, 1949, illustrate the anomaly. The first flare was accompanied by an S.I.D. The second flare, which broke out about three hours later, was more intense, covered about three times the area of the first flare, and lasted for a longer time, but there was no report of an S.I.D. for the period of its occurrence. It is possible that the flares are really nothing but symptoms of a more deep-seated phenomenon that produces S.I.D.'s. On the other hand, the answer may be found in physical differences between different types of flares. At present most flares are described by two numbers. One is an estimate of the intensity at maximum brightness and the other describes the area of the disturbance. What is needed is more detailed information such as precise measurement of the variation of intensity with time together with photographs of the flare spectrum. Both types of studies are under way at the McMath-Hulbert Observatory. Dr. Dodson is using a specially constructed flare densitometer to determine the light curves of flares with high precision. Preliminary results show that the light curves of different flares are by no means identical. Some flares show a very steep rise to maximum whereas others brighten more slowly. It is possible that studies of this type will result in more precise correlation between solar flares and ionospheric disturbances.

Observations of the spectra of prominences and flares are also in progress. Ideally one would like to cover on a single photographic plate the widest possible spectral region with the highest possible dispersion. With conventional spectrographs it is possible to achieve either high dispersion or large coverage, but not both simultaneously. For example, with the Littrow-type spectrograph in the McGregor tower, approximately 900 angstroms of the solar spectrum can be photographed on an 18-inch plate with dispersion of 2A/mm. As was mentioned earlier, however, the experiments that Dr. McMath and his associates have been making with the Harrison echelle grating indicate that it may be possible to register something like 3000 angstroms on one plate with a dispersion of several millimeters per angstrom. The design of the echelle grating by Harrison may well result in revolutionizing the art of solar spectroscopy.

The third branch of our solar research program is concerned with high-resolution studies of the infra-red solar spectrum, under the supervision of Dr. O. C. Mohler. Until a few years ago the solar spectrum could be studied with high dispersion only to an infra-red limit of about 14,000 angstroms. It is at this

point that the sensitivity of the photographic plate becomes effectively zero. The development of the lead sulfide photocell by R. J. Cashman has enabled us to extend high resolution observations of the spectrum to about 36,000 angstroms. There are many reasons why this region of the spectrum is important for the analysis of the solar and terrestrial atmospheres. First of all, the solar lines that appear in the spectrum are almost all of

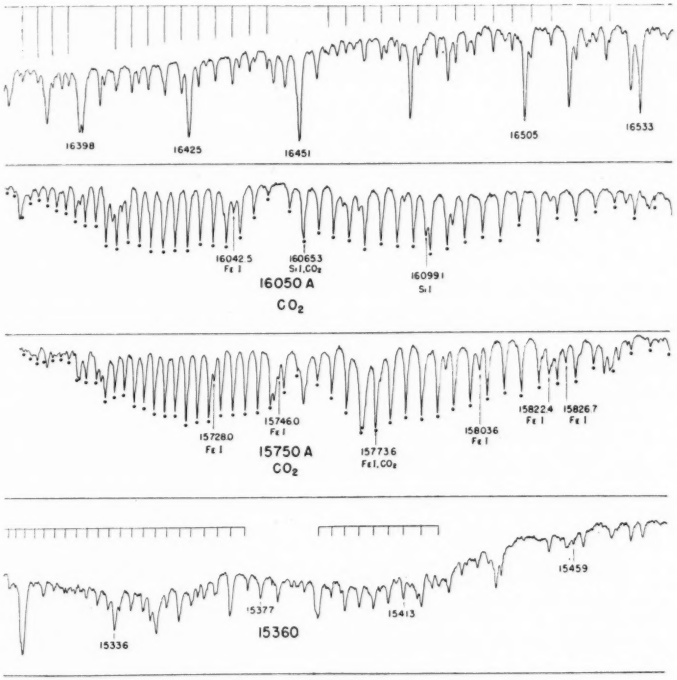


FIG. 8. Portions of the Infra-Red Solar Spectrum in the Neighborhood of 16,000 angstroms.

The closely spaced lines indicated by dots and vertical lines arise from carbon dioxide in the earth's atmosphere. The strong lines labeled with wave lengths in the upper section of the figure are due to methane, also in the earth's atmosphere. A number of solar lines of neutral iron and silicon are also labeled.

high excitation. Analysis of the intensities of these lines therefore provides information on the deep high-temperature layers of the solar atmosphere. Second, the passage of infra-red sunlight through the earth's atmosphere is impeded by the absorption of atmospheric molecules. In many regions of the spectrum the absorption is substantially complete and produces total opacity. In other regions, the molecules produce well-defined patterns of lines (see Fig. 8) whose intensities can be measured and analyzed to yield important information on the earth's atmosphere. Among the molecules that may be studied in this way I may mention carbon dioxide and its isotopes involving C^{13} and O^{18}, methane, nitrous oxide, and water vapor.

Analysis of the intensities of the molecular lines can provide the following information: (1) the abundance, (2) the vertical distribution of the gas, and (3) the temperature gradient. It turns out that the abundance and vertical distribution can be determined with very good accuracy, but that the temperature gradient is relatively indeterminate unless the measured intensities are of the very highest precision.

As a corollary to the infra-red studies, we have found it necessary to obtain the laboratory spectra of the various molecules that occur in the earth's atmosphere. These laboratory spectra have a twofold purpose: first, they facilitate the identification of lines in the solar spectrum (as Fig. 9 illustrates in the case of nitrous oxide) and second, they make possible the measurement of theoretical intensities or transition probabilities without which the analysis cannot be carried out. Fairly precise abundances have been determined for both methane and nitrous oxide. The total quantity of methane in the earth's atmosphere is equiva-

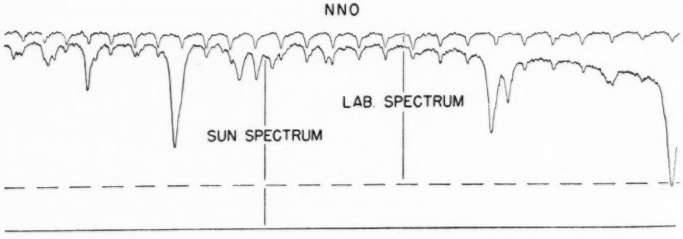


FIG. 9. Lines of Nitrous Oxide as Observed in the Laboratory and in the Solar Spectrum at 21,300 angstroms.

lent to that which would be contained in a layer 1.2 cm thick at normal temperature and pressure, whereas the figure for nitrous oxide is about 4 mm. Similar determinations of the abundance of carbon dioxide and its isotopes are in progress. Thus far, we have not been able to detect seasonal variations in the abundance of methane. It will be interesting to learn whether such variations occur in the abundance of carbon dioxide, inasmuch as carbon dioxide is used by plants in the summer and thrown out by heating systems in the winter.

The vertical distribution of methane in the earth's atmosphere has also been investigated. In this respect a comparison of observations made at Michigan and at an altitude of 6,000 feet at the Mount Wilson Observatory has been very helpful. It seems well established that the distribution of methane through the atmosphere is world-wide in character and that its density falls off exponentially with height at the same rate as the main body of the atmosphere. The results for nitrous oxide and water vapor are not yet available.

The determinations of abundance and vertical distribution of the atmospheric molecules should provide information both on the origin of the rare constituents of the atmosphere such as methane and nitrous oxide and also on the temperature balance of the atmosphere. The temperature gradient of the earth's atmosphere is established as the result of a rather complicated process of absorption and emission of radiation. Ultraviolet radiation from the sun is absorbed by ozone in the earth's atmosphere and infra-red radiation from the surface of the earth by ozone, water vapor, and carbon dioxide. Conversely, the atmosphere loses energy by infra-red emission of ozone, water vapor, and carbon dioxide. If the abundances and vertical distribution of the various gases are known, along with the absorption coefficients, it should be possible to calculate the atmospheric temperature gradient. Strong and Plass at Johns Hopkins have recently made calculations of this type that seem to provide a logical explanation for the existence of the tropopause, but more accurate data are needed on the vertical distribution and the line absorption coefficients.

The preceding text has sketched briefly just a few of the observational problems of solar physics and indicated the way in which these problems are attacked at one observatory. It is our hope that the concerted attack on the solar problem by many solar observatories may yet serve to bring the sun into the service of man.

INFLUENCE OF THE SUN UPON THE IONOSPHERE

NEWBERN SMITH
National Bureau of Standards

Radio science has first terrestrial claim to the light radiation of the sun. Before solar energy is available for photosynthesis or the breeding of forests or the heating of homes or for influencing the weather, it must pass through a series of filters in the earth's atmosphere which, fortunately for us, intercept the portions of the sun's radiation that would be extremely harmful to life. The first few of these filters are the electrically charged layers in the upper atmosphere, which we know as the ionosphere, and which range from perhaps 500 miles down to about 50 miles above the earth's surface. Their absorption is, again fortunately for us, quite selective; the ionosphere leaves a large window in the solar spectrum between about 2000 angstroms and 30 meters wavelength so that biologists and meteorologists will have something to work with.

But in addition to its protective role, the ionosphere is of service to man in a strictly utilitarian manner. It aids man's service to man. Communication between human beings is a fundamental of civilization as we know it, and speedy communication by radio signals is greatly facilitated by the ionosphere. The propagation of radio waves over long distances becomes possible and convenient when man makes use of the ionosphere as one radio mirror and the ground as another. And it is the sun which maintains the ionosphere mirror, and it is solar activity which determines its characteristics and the effectiveness with which it reflects and guides radio waves.

Let us orient ourselves briefly (Fig. 1). We recognize two general regions overhead in the ionosphere — the E at about 100 km., the F nominally at, say, 250 km. We distinguish the regions by the variation with height of the effective density of free electrons. In each of these regions there is a height at which the electron density reaches a maximum (Fig. 2); sometimes there are several maxima or layers within a region. The electron density of the highest layer is the greatest, i.e., present observational techniques do not permit the detection of a low density layer at a greater height than one of higher density. In other words, we cannot see a short man standing behind a tall man.

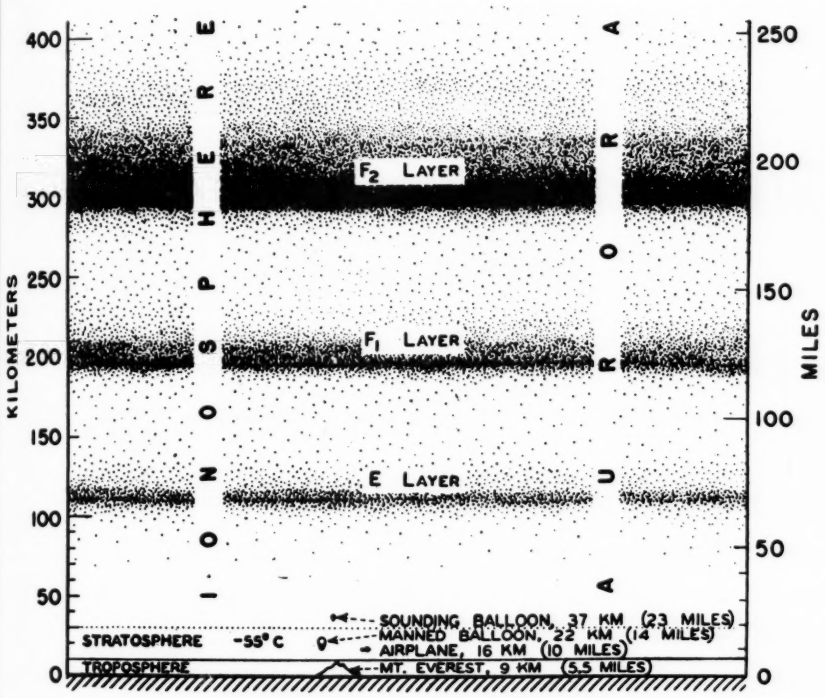


FIG. 1. Physical Features of the Earth's Atmosphere.

Both the height above the earth of these maxima and the magnitude of the electron density are greatly variable with time and geographical location. Explaining and predicting these changes is one of the important jobs of the National Bureau of Standards.

Let us see how much of this we can attribute directly to the sun. Fig. 3 is a typical curve showing the diurnal variation of the electron density of the ionospheric layers. The lowest curve shows the electron density for the E-region at the height — about 110 km. — where the density is a maximum. The ordinates of the graph are expressed in megacycles; in radio we generally talk about a quantity called "critical frequency", which is proportional to the square root of the maximum effective electron density of a region.

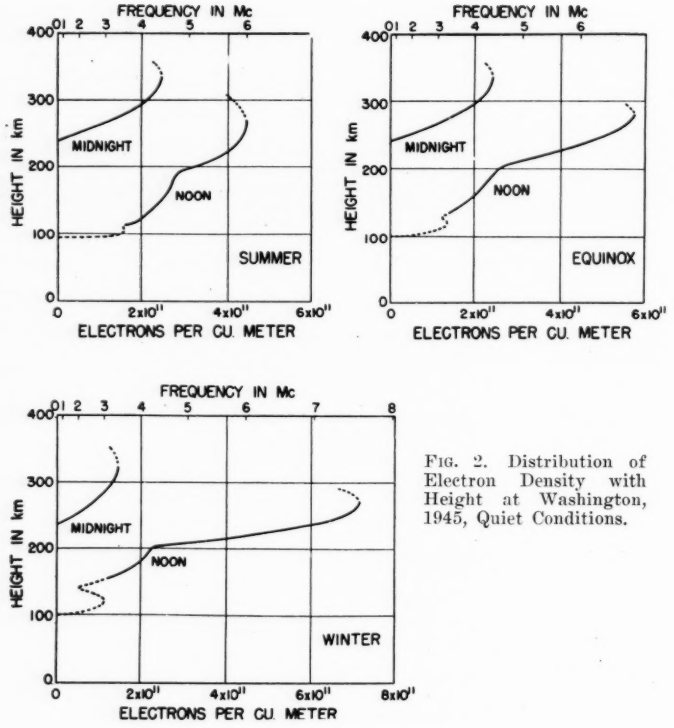


FIG. 2. Distribution of Electron Density with Height at Washington, 1945, Quiet Conditions.

The diurnal variation of E-region critical frequency is very large. It has a maximum at near noon, and nighttime values are too low to measure by routine techniques. It is obvious that the E layer critical frequency depends on the altitude of the sun; indeed the equation ($f^{o}E = A + B \cos^{n} X$) will represent the observations at any one station on any given day very closely. The midday maximum has over and again been shown to depend very closely on the altitude of the sun at noon, regardless of season or geographical location. Note that the curve is symmetrical. It is apparent that the intensity of solar radiation, and hence the energy available for electron production, would vary closely with the angle of incidence of the radiation upon the layer. The *net* electron density is seen to follow the changing altitude

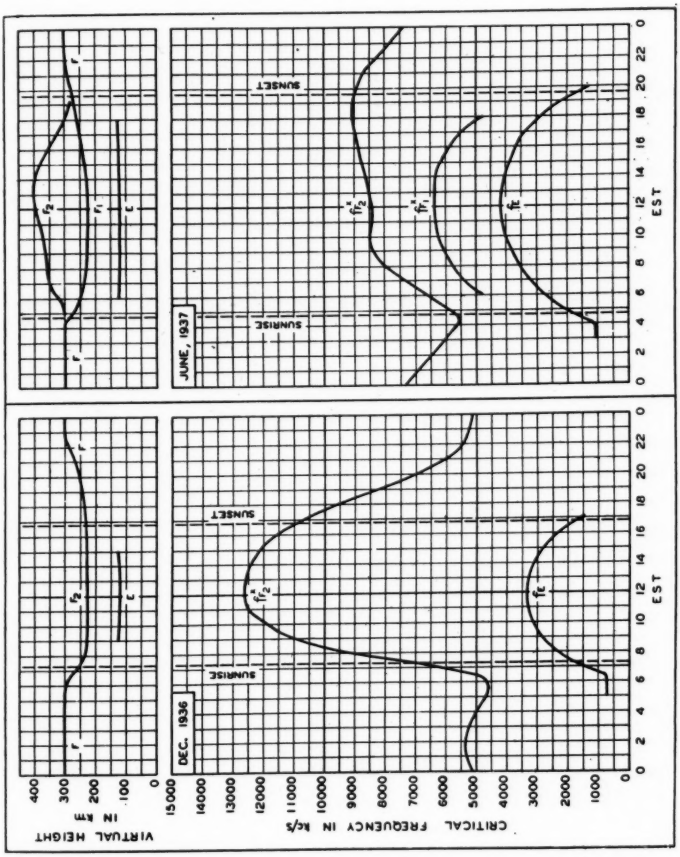


FIG. 3. Typical Diurnal Curves of Virtual Height and Critical Frequency.

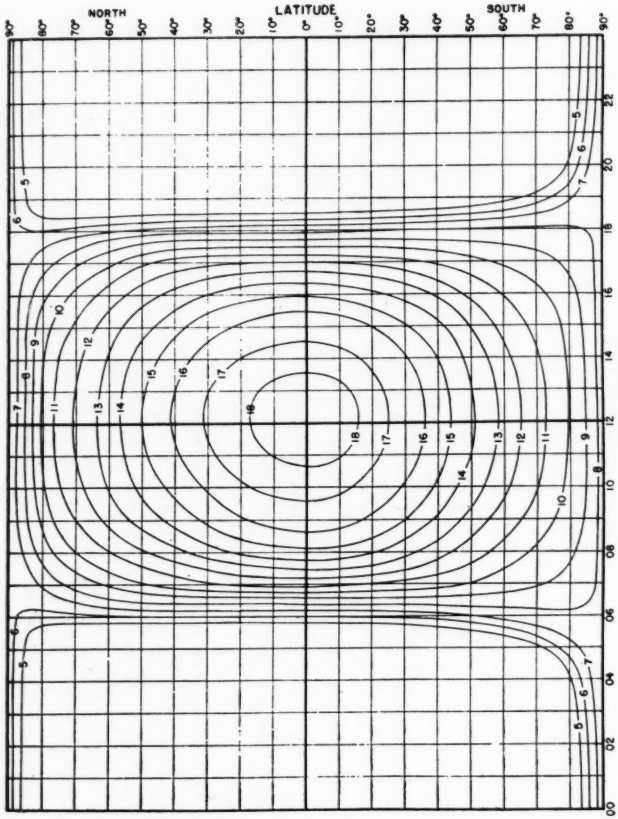


FIG. 4. Typical Configuration of E-Region with Latitude and Local Time.
(Numbers are proportional to critical frequency.)

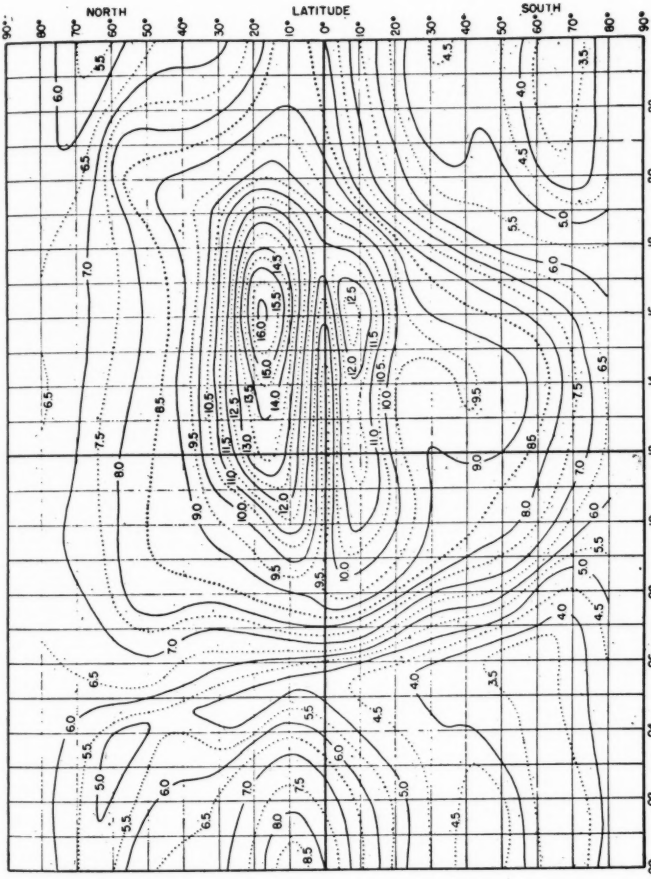


FIG. 5. Typical Configuration of F2-Layer Critical Frequencies.

of the sun without an appreciable time lag. This indicates that the rate of disappearance of free electrons in the E-region is very large compared with the rate of production.

In the F-region there are normally during daytime two layers, F1 and F2; at night there is usually only a single height of maximum electron density, i.e., a single layer. The F1-layer is generally similar to the E-layer, and is also evidently a sunlight layer. The critical frequency of the F2-layer is systematically greater, usually much greater by day than by night. The diurnal variation, however, is not symmetrical; the maximum is not in general at noon. But in the F2-layer the rate of *production* of free electrons depends closely on the intensity of incident solar radiation. The rate of disappearance is much slower so there is time for electrons to accumulate and to be affected by the earth's magnetic field. Also since the F2-layer has a variable half-thickness of 50 to 200 or more kilometers, the critical frequency is not a good measure of the total electron production caused by solar radiation.

Fig. 4 shows another way of visualizing the effect of solar radiation in producing the ionospheric layers. The contours show the configuration of E-layer critical frequencies as a function of latitude and local time. The numbers on the contours are proportional to the critical frequencies. They are seen to be symmetrical, with the greatest critical frequencies in the neighborhood of the sub-solar point. A similar set of contours for the F2-region (Fig. 5) shows well the abrupt increase after sunrise and the generally larger critical frequencies in daytime. It is evident that the intensity of incident solar radiation is not the most important factor determining critical frequencies except in the morning period.

At this point the D-region of the ionosphere should be mentioned. This is a region of ionization low down in the ionosphere where the collisional effects of electrons with atmospheric gas molecules are very important. The effects of this region are chiefly manifested by absorption of the energy in the radio waves and a consequent weakening of the radio signals. The ionization density in this region is also in phase with the sun's zenith angle, reaching a maximum at midday. No direct measurements of critical frequency or maximum ion density for this region can be made at present, but there is evidence that they would follow laws similar to those for the E-region ionization.

So far we have taken a very idealized view of the sun's effect on the ionosphere. The illustrations are intended mostly as a

reminder of the types of normal effects which an earthbound observer can detect by means of radio soundings. We have not gone into the matter of how solar radiation may produce the observed electron density distributions; this is an intriguing topic in itself, but one which is quite confused and uncertain at the present time.

Let us now explore the effects of the sun upon the ionosphere which in turn affect its utilization by man for radio communications. You will see later that sometimes the sun and the ionosphere do man a disservice as well as a service.

The above idealized (and oversimplified) picture of the ionosphere is subject to drastic variations with time. These occur because there are important changes in the quantity and quality of solar radiation and also because of indirect solar effects, such as magnetic storms. A few non-solar influences, notably lunar tides, also play a part in the variations of ionospheric characteristics. In discussing the more direct effects, types of solar activity may be separated into three classes:

(1) Long-term, that is, steady changes over a period of several years.

(2) Short-term, or about the lifespan of a sunspot region — up to a few months.

(3) Outbursts, such as a flare, lasting up to a couple of hours.

Let us take some examples:

Between the low and the high stage of the 11-year solar activity cycle, the critical frequency of the F2-layer for the same time of day and season may be as much as doubled (Fig. 6). This means, you will recall, a fourfold increase in the maximum electron density of the layer. For communications, it means about a 2:1 difference in the useful range of radio frequencies for a given circuit. The level of solar activity sets the limit of the range of useful radio frequencies for communication. At the low stage of the cycle, this useful range is uncomfortably compressed. You can see why radio people are interested in obtaining good measurements — and predictions of long-term solar activity.

Astronomers have provided many indexes of solar activity, such as sunspot numbers, prominence numbers, character figures of flocculus activity, sunspot areas, and coronal indexes. Thus far we have found the strongest correlations when we compared critical frequencies with sunspot numbers using long-term averages of each. It is surprising that sunspot numbers have proved the best index for these purposes; as is well known, the sunspot number is a quite arbitrary index and is rather sub-

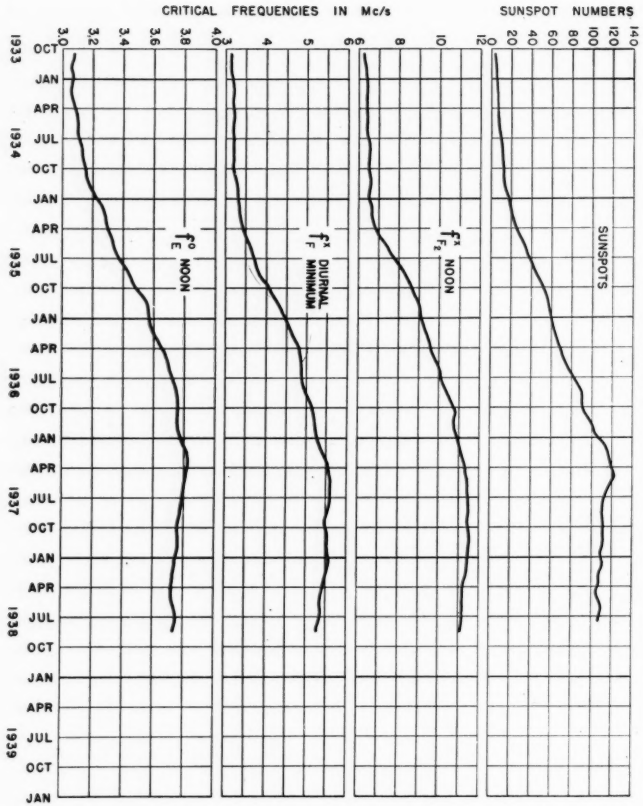


FIG. 6. Comparison of Sunspot Numbers and Critical Frequencies — 12-month Running Averages, 1933-1939.

jectively derived from visual observations with a small telescope. Analyses have shown, however, that the correlation is weaker when the analysis takes for the solar index the total spotted area, which should be a more nearly repeatable measurement. Correlations involving monthly average F2 critical frequency and 12-month smoothed relative sunspot numbers yield correlation coefficients of about 0.90, 0.95 or greater. When total

spotted area is the solar index, the coefficients are about 0.05 lower. It is of interest to note that shorter term averages of these indices and characteristics correlate less well — the daily values hardly at all.

Short-term solar variations also affect the ionosphere, but here the influence is largely indirect. It is true that an abrupt change in the abnormal level of solar activity can be detected in measurements of critical frequencies within a period of a month or two. This is, however, only a partially resolved consequence of the long-term effects we have just discussed. The indirect effects, however, are very pronounced. It is a common occurrence that soon after the development of a large, active sunspot region on the visible disk, there are marked differences between observed and expected ionospheric characteristics. Anomalies also occur when an active solar region is situated near the center of the sun's disk or in some other empirically determined preferred position on the disk. Usually there is a simultaneous magnetic storm. It is probable that the observed ionospheric effects which we call an "ionosphere storm", are a consequence of the abnormal current systems in the upper atmosphere which produce the observed magnetic effects, rather than a result directly of changes in incident solar radiation.

Again the location and nature of the abnormal solar radiation is obscure. Clues continue to be accumulated, and it is only within the past year that the worth of activity indices deriving from newly developed observing techniques has been able to be put to a test. At the National Bureau of Standards the progress of solar activity is followed day by day, utilizing all available observations. The criteria of unusual activity of a sunspot region — a large spot area, strong magnetic field intensities, unusual spectroheliographic measurements, large intensity of coronal emission — are now supplemented by observations newly available on a systematic basis. The yellow coronal line has been observed to be intense over many sunspot regions which proved to be significantly active. As evidence of instability and hence potential activity in a region, we have with some success taken abnormal ratios of coronal line intensities. Usually the green coronal line is about five times as intense as the well-known red line. If the two lines are of nearly the same intensity or the red is more intense than the green, the underlying solar region has more often than 'chance' proved to be significantly active. Perhaps the most important newly available index of solar activity is the so-called "flare-ette". These are chromospheric eruptions

which have light curves and other characteristics similar to flares, except that the maximum intensity is relatively small. Other solar indices are coming from systematic radio noise measurements of the sun. All these indexes serve to provide empirical relationships between the sun's activity and magnetic and ionospheric storms. The accompanying ionospheric effects at a single location would be evidenced by unusual diurnal curves of critical frequency and other parameters. These would appear to be indirect consequences of the solar activity.

One of the most striking effects of the sun on the ionosphere is the relation between bright chromospheric eruptions or solar flares and a greatly increased but short-lived absorption of radio waves in the D-region. This was one of the first direct evidences to be found of the effects of the sun on the ionosphere. The ultra-

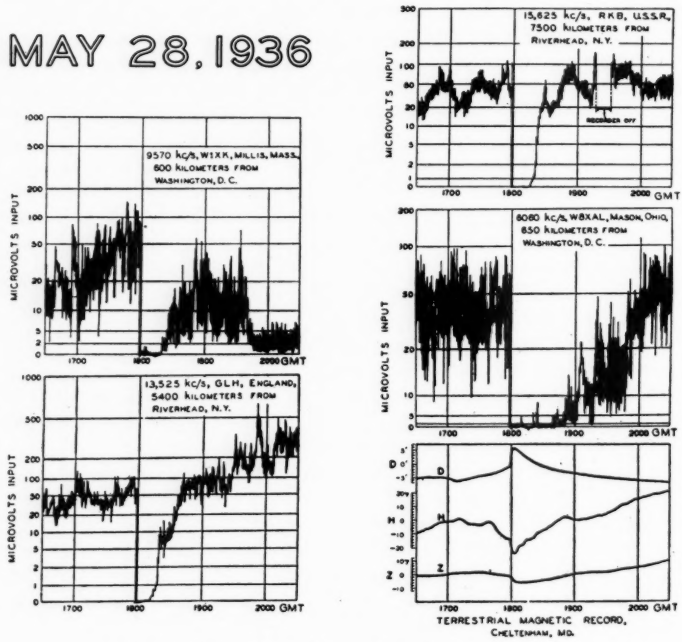

MAY 28, 1936
9570 kc/s, W1XK, MILLIS, MASS. 600 KILOMETERS FROM WASHINGTON, D.C.
13,525 kc/s, GLH, ENGLAND, 5400 KILOMETERS FROM RIVERHEAD, N.Y.
15,625 kc/s, RKB, U.S.S.R., 7500 KILOMETERS FROM RIVERHEAD, N.Y.
RECORDER OFF
6080 kc/s, W8XAL, MASON, OHIO, 650 KILOMETERS FROM WASHINGTON, D.C.
MICROVOLTS INPUT
GMT
D
H
Z
TERRESTRIAL MAGNETIC RECORD, CHELTENHAM, MD.

FIG. 7. Signal Intensity and Magnetic Records during Chromospheric Eruption.

violet radiation from the solar flare appears to produce an increase of ionization in the absorbing D-region of the ionosphere, often severe enough to produce a complete blackout of radio transmission at all high frequencies on the daylight side of the globe (Fig. 7). Associated with this sudden ionospheric disturbance is usually a disturbance of the earth's magnetic field, of such a nature as to constitute an augmentation of the normal quiet-day variations of the earth's field. It appears as though the intensity of the flare is of considerably greater importance than its area in producing these effects, although much remains yet to be found out concerning the relationships between the magnitude of the flare, the amount and duration of the ionospheric absorption and the associated terrestrial magnetic effect. For example, some flares produce intense ionospheric absorption but only very slight magnetic effects; whereas other flares which produce marked terrestrial magnetic effects may be associated with only moderately severe increases in ionospheric absorption.

In conclusion, you are reminded of the principal effect of the sun upon the ionosphere: the sun produces and largely maintains the ionization in the ionospheric regions — the E-region, the F-region and the D-region and perhaps other as yet undiscovered regions which are not readily observable by radio sounding techniques. The additional effects which most concern man and his radio communication problems are those of varying solar activity, on a long and short time scale. Many of these effects are large and have economic consequences and, it must be admitted, have yet to be satisfactorily explained.

LOW-FREQUENCY NOISE DISTURBANCE

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INTRODUCTION

Vast quantities of observational data and several theoretical papers have appeared on the subject of solar noise in the radio-frequency spectrum. The work has covered the radio-frequency band from 9 megacycles to microwave regions. Very few papers have appeared on radiation in the low-frequency region. This radiation may be the product of solar or ionospheric phenomena. Measurements of the reception of energy in the band 5 to 1,000 cycles per second have been made.

Initial work was done by Menzel and Salisbury, [1, 2] who noted a great enhancement of noise in the low-frequency audio regions. Electric field intensities of the order of 1 to 100 volts per meter were reported in the frequency range 25 to 300 cycles per second.

Willis[3] corroborated the basic results of these first measurements. He employed two bucking coils and an amplifier to establish field intensities considerably higher than those from possible artificial sources. Willis made his measures at a remote station, where he set up two pick-up coils and a wave analyzer of 4 cycles band width. The intensities Willis received were lower than those previously reported by Menzel and Salisbury. The range varied (Figure 1) from electric field intensity of 1.8 millivolts per meter at 5 cycles per second to a value approaching the noise level of the analyzer at about 1,000 cycles per second.

With these two experiments completed, work to fit low-frequency noise in with terrestrial and solar phenomena was in order. The timing of any enhancement of this noise should be correlated with geomagnetic disturbances. A complete picture of the sequence of events plus other physical facts should help to clarify the problem and contribute to an understanding of the complex geophysical phenomena of a magnetic and electromagnetic nature.

The experiment initiated by the Upper Air Laboratory of the Geophysical Directorate was designed to provide continuously

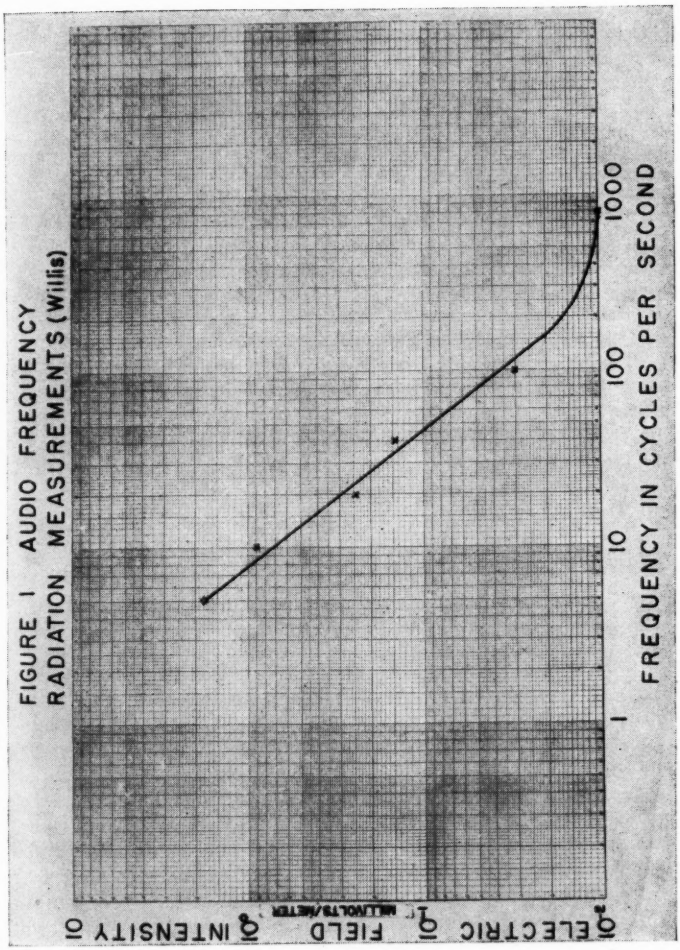
FIGURE 1 AUDIO FREQUENCY
RADIATION MEASUREMENTS (Willis)
ELECTRIC FIELD INTENSITY
MILLIVOLTS/METER
1
10
100
1000
FREQUENCY IN CYCLES PER SECOND

operated recordings of noise in the frequency band 0.5 to 15 cycles per second. The pick-up mechanism consisted of a coil containing a large number of turns. A preamplifier and a high-level amplifier were used in conjunction with a slow-speed Brush recorder to take the data.

The site chosen was the Seismograph Building of the Harvard Observatory at Harvard, Mass., a relatively noise-free location. The initial checks were designed to determine the possibility of correspondence between low-frequency noise and seismographic data. The coil's vibration from earth waves was for the most part inadequate for the unit's use as a seismograph. Only extremely violent earthquakes or blasts from a nearby quarry affected the equipment.

Measurements

The first basic measurement led to a determination of the level of the signal (low-frequency noise disturbance) above the inherent noise of the amplifier and pick-up. The average value obtained for the "quiet" periods was of the order of 0.62 microvolt, which corresponds to an electric field intensity of approximately 10 millivolts per meter. The low point of intensity was of the order of 2 millivolts per meter.

The amplifier modifications, which were necessitated by the fact that a strong pulsed signal could force the galvanometer pen from its pins on the recorder, brought about a limiting of maximum signal to approximately 10 microvolts or 100 times "quiet" period noise. This peak level occurred continuously during several very disturbed periods of observation. Occasional sporadic pulses during mildly disturbed periods also caused the instrument to exceed this peak value. During some of the intervals of extreme activity, peaks exceeding the normal level by a factor of more than 100 times were detected through input attenuators. The problem of noise measurements in the field is complex at these low frequencies. Measuring the noise level of the system within the laboratory, under shielded conditions, gives figures not obtainable under actual operating field conditions. Within the confines of any one area, nearby electrical equipment such as switches, relays, motors, electronic gear (audio oscillators, receivers, etc.) contribute to the recorded noise level. Recent work on shot effect and low-frequency noise voltages makes it necessary to use a subtraction technique to determine the exact contribution that sources of external radiation may contribute to the overall signal.

Solar Disturbance

On February 13, 1950, Harvard Observatory reported a series of spots spread across a quarter of the face of the sun. The disturbance was termed the "largest sunspot in years". Cornell University, operating on 205 mc with its radio telescope equipment, noted a small increase of noise on the 13th but recorded a tremendous increase when it started operations on the 14th (Figure 2); a decrease followed with a small amount of fluctuation centered about a large steady-state value of solar radio noise. On the 18th, however, a large increase in base level occurred, followed shortly thereafter by a sharp decrease.

Cornell's radio noise thus seemed to possess a double-humped curve with a small dip between the two peaks and rather steep sides.

The Cheltenham K indices for the period February 17 to 26 appear in Figure 3. They display a fast rise in value to a large peak with a Number 7 disturbance. The rise, which commenced at 1400 GCT on the 20th of February, reached a peak at approximately 1900. A small decrease thereafter was followed by an increase to a peak of 6 at approximately 1200 GCT 23rd February. From February 20th on, for several days, numerous ionospheric storms resulted in extremely erratic radio transmission.

The observed low-frequency noise displayed the twin hump pattern shown by geomagnetic indices and by solar noise (Figure 4), although the time between peaks is not constant. The low-frequency pattern preceded geomagnetic values by approximately 19 hours. The normal level of 6 to 10 millivolts per meter rose to a level of 80 millivolts per meter which was reached at 2300 on the 20th of February. The number of bursts increased tremendously during the period as the entire character of the signal changed. Figures 5 and 6, which are direct tracings of the records, are striking evidences of the storm bursts.

Low-frequency noise measurements started to increase at 2100 on February 19th and reached a peak value some 5 hours later. The rise time of the initial burst corresponded closely with the rise time of the geomagnetic index. A slow drop occurred shortly after 0500 on the 20th, followed by a second rise.

Thus the two functions, geomagnetic index and low-frequency noise, followed in this particular case the same general curve but displaced in time. The rise time of each was approximately the same. The geomagnetic index rose later than the low-frequency noise and ended later.

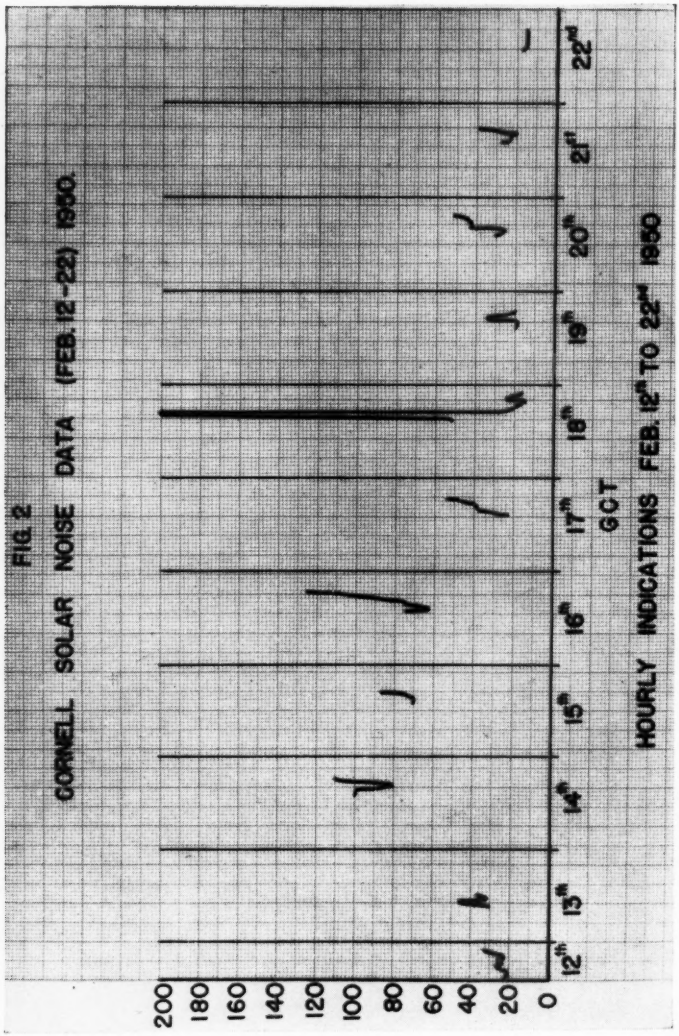
FIG. 2
CORNELL SOLAR NOISE DATA (FEB. 12-22) 1950.
200
180
160
140
120
100
80
60
40
20
0
12th
13th
14th
15th
16th
17th
18th
19th
20th
21st
22nd
GCT
HOURLY INDICATIONS FEB. 12th TO 22nd 1950

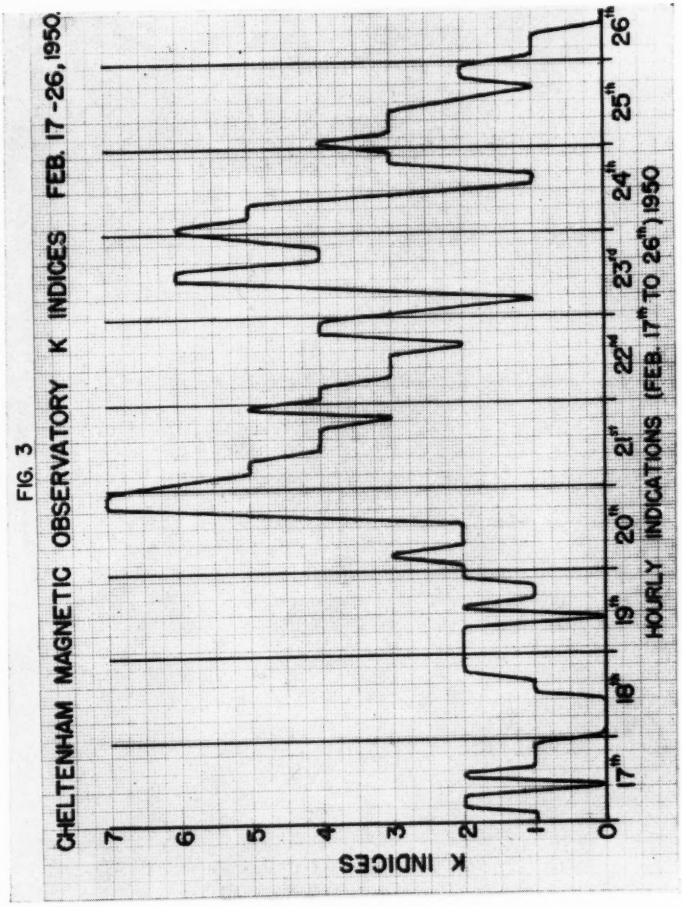
CHELTENHAM MAGNETIC OBSERVATORY K INDICES FEB. 17-26, 1950.
K INDICES
0
1
2
3
4
5
6
7
17th
18th
19th
20th
21st
22nd
23rd
24th
25th
26th
HOURLY INDICATIONS (FEB. 17th TO 26th) 1950

FIG. 3

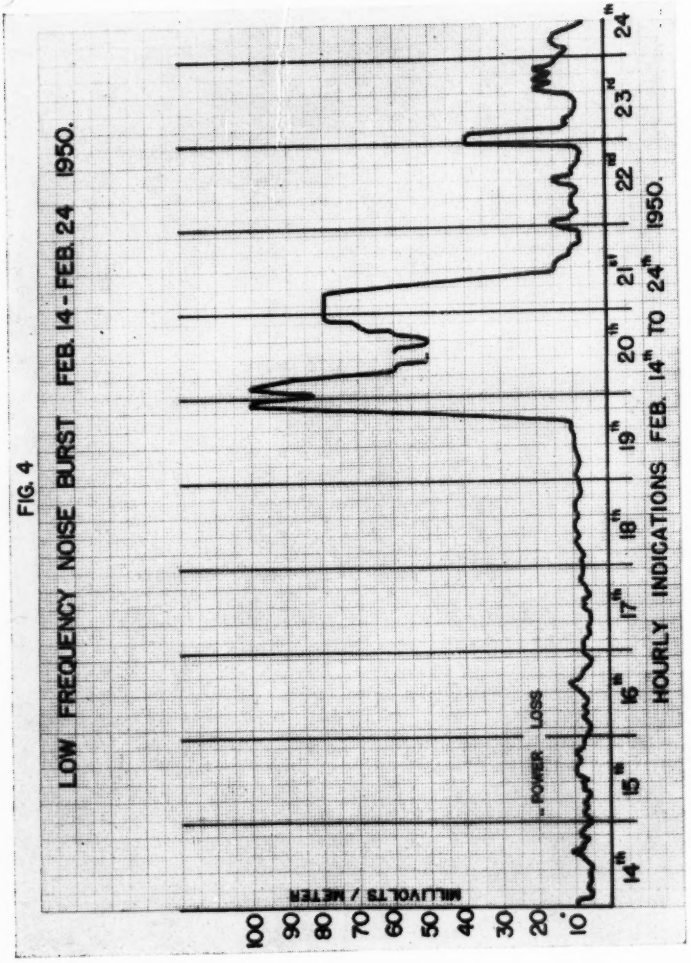
LOW FREQUENCY NOISE BURST FEB. 14 - FEB. 24 1950.
MILLIVOLTS / METER
100
90
80
70
60
50
40
30
20
10
POWER LOSS
14th
15th
16th
17th
18th
19th
20th
21st
22nd
23rd
24th
HOURLY INDICATIONS FEB. 14th TO 24th 1950.

FIG. 4

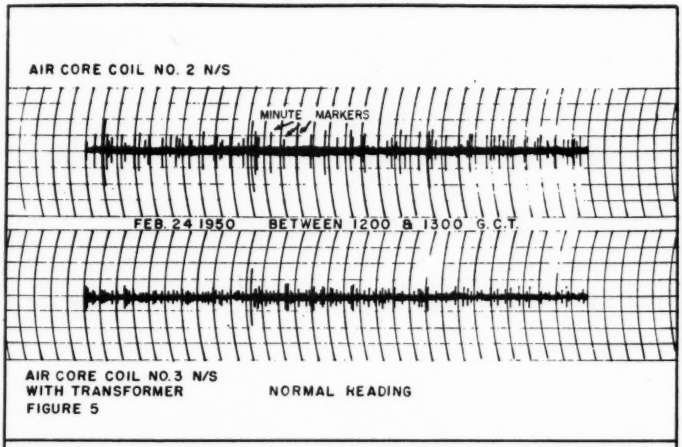
AIR CORE COIL NO. 2 N/S
MINUTE MARKERS
FEB. 24 1950 BETWEEN 1200 & 1300 G.C.T.
AIR CORE COIL NO. 3 N/S
WITH TRANSFORMER
NORMAL READING

FIGURE 5

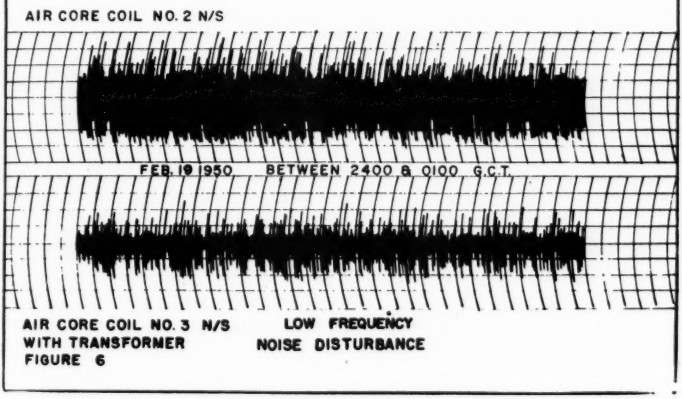
AIR CORE COIL NO. 2 N/S
FEB. 19 1950 BETWEEN 2400 & 0100 G.C.T.
AIR CORE COIL NO. 3 N/S
WITH TRANSFORMER
LOW FREQUENCY
NOISE DISTURBANCE

FIGURE 6

It must be stressed that this detailed analysis is for a single example. Different amounts of delay between geomagnetic storms and low-frequency disturbances have been recorded. Further data are needed to assess the seasonal variations and the types of storms. In general, geomagnetic storms follow low-frequency noise storms by various intervals. Several geomagnetic storms, however, have occurred simultaneously with low-frequency noise storms.

The intensity of geomagnetic storms is not always matched by the levels of the low-frequency disturbances. A low-frequency rise always accompanies each geomagnetic disturbance but without a one-to-one duplication of intensity level. Occasionally a severe geomagnetic disturbance may possess only a minor rise in the associated low-frequency noise.

Diurnal Variations

Daily variations in amplitude were recorded, but the diurnal pattern is extremely difficult to assess. The changes were very small in magnitude, although definite. Figure 7 is a chart of the diurnal variations of electric field intensity during a quiet period, December 19 to 22, 1949.

Although the record indicates a general pattern of rise until 2400 Universal Time and a decrease in the forenoon, such fluctuations are not universal. Diurnal swings from 2 millivolts per meter to 10 millivolts per meter are normal.

A more comprehensive study of the low-level problem is being initiated at Maynard, Mass., which area seems to be relatively freer from artificial sources of noise. Interference from observatory equipment takes place sporadically at the Harvard, Mass., site.

Equipment

The inductance coil for picking up the radiation in the range of one-half to 15 cycles per second was composed of 100,000 turns of #40 wire. The inductance was 375 henries, determined by ringing methods of measurements. Its self-resonant frequency was considerably higher than the frequency range utilized.

Although the coil had an air core, a permalloy rod could be inserted as an accessory. This rod acted as a non-linear amplifier for the earth's magnetic field since permalloy has the property of increasing the inductance of a coil with low values of magnetic field. Changes in the earth's magnetic field were amplified.

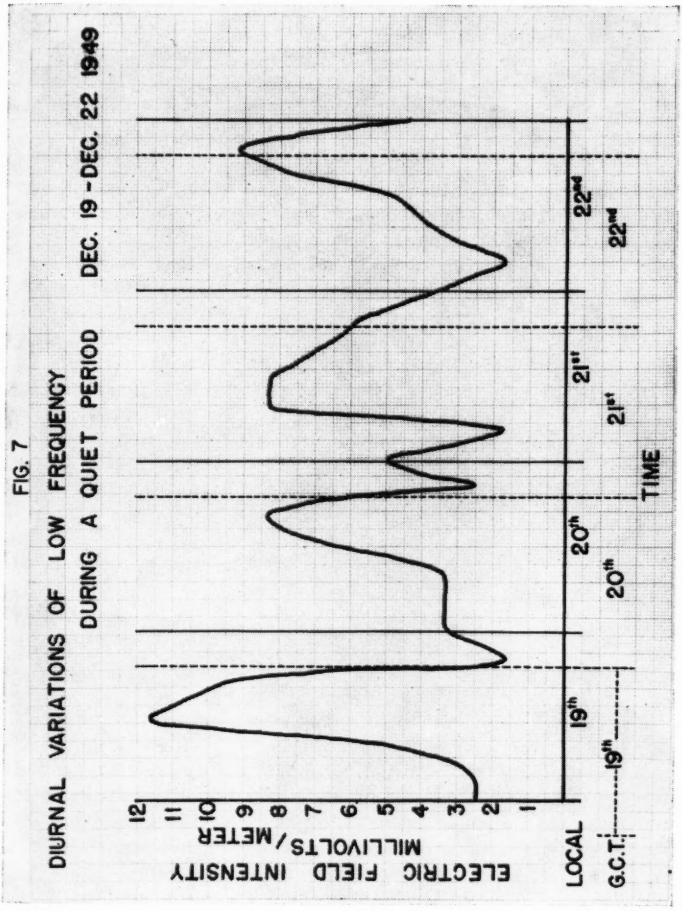
FIG. 7
DIURNAL VARIATIONS OF LOW FREQUENCY
DURING A QUIET PERIOD DEC. 19 - DEC. 22 1949
ELECTRIC FIELD INTENSITY
MILLIVOLTS/METER
12
11
10
9
8
7
6
5
4
3
2
1
LOCAL
19th
20th
21st
22nd
TIME
G.C.T.
19th
20th
21st
22nd

This approach (with and without a permalloy rod) yields a ready-made correlation between changes in the earth's field and low-frequency noise levels. The Brush two-channel recorder was used to show two coils in operation, one with and one without the rod. There is general correspondence in response between the two (Figure 8). However, adding the permalloy rod to the coil system increased the noise values and also increased the variability of the pickup. Since changes in the earth's magnetic field of long periods were to be isolated from low-frequency noise disturbances, the rod was discarded after a short run. The increase in general variability of short duration in the coil with rod is apparent from Figure 8. Figure 9 illustrates the general calibration techniques. A shielded wire-wound resistor equal to the coil resistance (220,000 ohms) was placed at the end of the cable to give a "dummy" input reading. Low-frequency noise was always a minimum of 0.2 microvolt above the 0.28 microvolt amplifier noise level.

Figure 10 is a block diagram of the system. One complete channel of the system was kept fixed. The coil, with its axis oriented North and South and set parallel to the earth's surface, was placed approximately 18 inches below the surface of the earth. Coil 2 (Figure 9) remained in this position for the entire experiment. The fluctuations picked up in the coil were amplified by a preamplifier (battery operated), fed into a filter designed to produce a 60-db attenuation in any 60-cycle signals coming through, and then fed into the Brush A.C. amplifier and oscillograph. A second channel containing the same elements was used for varying the input signal.

Other Aspects of the Measurements

It was very evident during the observations that electrical activity in hurricanes, thunderstorms, etc., affected the equipment as well as the disturbances more readily traceable to geophysical or solar origin. Correlations are not available at the present time for such data. The nature of the hurricanes and thunderstorms will be investigated. Time-and-distance measurements will be made in correlation with sferics data.

Of special interest is the occasional reception, at certain periods, of bursts of almost pure sine waves. A careful check was made for possible generation of these frequencies inside the equipment; several characteristics indicate, however, that these audio tones do not arise from amplifier difficulties. The frequencies are not constant. Even during a single one-minute burst,

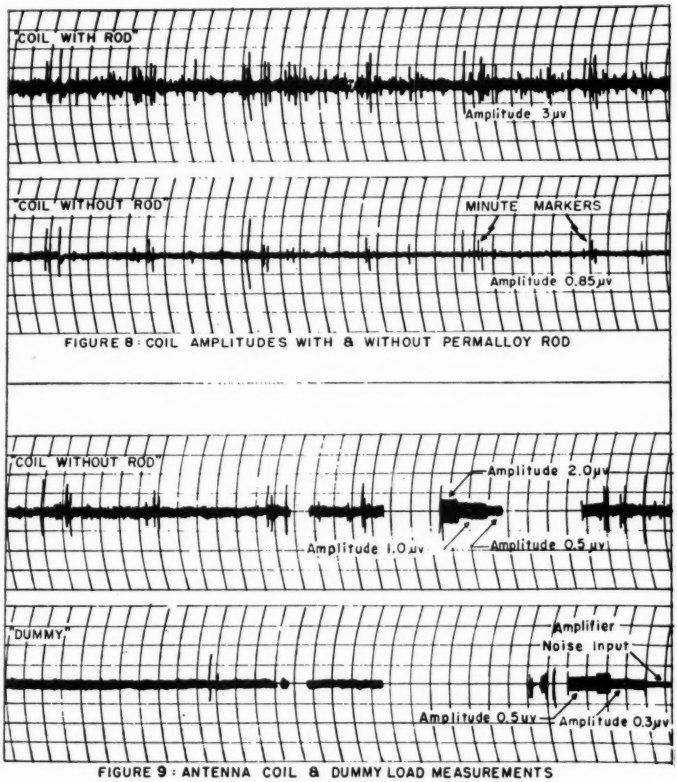

FIGURE 8: COIL AMPLITUDES WITH & WITHOUT PERMALLOY ROD

FIGURE 9: ANTENNA COIL & DUMMY LOAD MEASUREMENTS

the period often changes by a factor of two. The burst durations are also irregular, and the frequencies shift erratically. Generally, during periods of great activity, series of quasi-periodic bursts follow one another for several hours at a time. Days of low activity may pass without the occurrence of a single burst of sine waves.

Of possible interest is the fact that some observers have reported occasional "whistles" that accompany high-frequency solar noise. These sporadic tone bursts also do not have the characteristics of random noise.

Causes

In recent work, Smith, Little, and Lovell[4] attribute the variable component of the noise source in Cygnus to ionospheric or interstellar disturbances. When two similar receivers of cosmic noise were placed over 210 km apart, the rapid fluctuations of intensity at the two receivers displayed no detailed correlation.

It is suggested that the variable component of the low-frequency noise, including the bursts and increased noise level, may lie in plasma-like oscillations of the ionosphere, which may generate the low frequencies whose observation forms the subject of this paper. The low-frequency oscillations may modulate the high-frequency noise from fixed sources such as Cygnus and

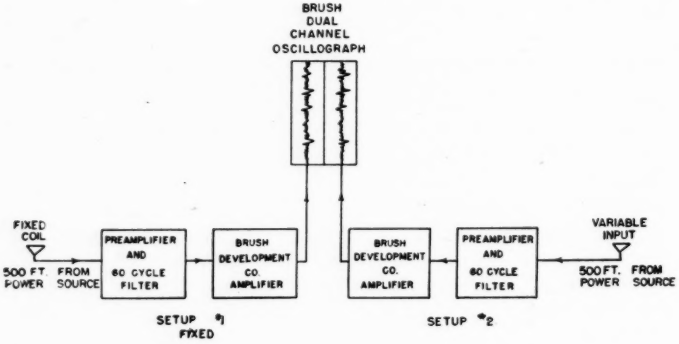

FIGURE 10 BLOCK DIAGRAM OF LOW FREQUENCY NOISE EXPERIMENTS

Sagittarius, and thus produce the audio components of the observed signal. In the case of low-frequency fluctuations, the signal comes directly from the plasma-like oscillations.

I would like to thank Dr. M. O'Day, Dr. D. Menzel, Dr. D. MacDonald and Dr. W. Salisbury for their encouragement and advice and Mr. Barney Emmons and Mr. Harley Baird for their assistance on the data taking and analysis.

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SOLAR VARIABILITY AND METEOROLOGICAL ANOMALIES

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1. INTRODUCTION

The earth's atmosphere operates as a giant heat engine that derives its energy almost entirely from the sun. Seasonal variations in the geographical distribution of this incoming solar energy explain the seasonal variations in our weather. Meteorologists understand these regular solar variations and recognize, at least empirically, the atmosphere's responses to them. Neither the general circulation of the earth's atmosphere nor its seasonal variations forms the subject of this discussion. Rather, we shall be concerned with *irregular* variations in solar energy, and their suitability as a contributing cause of irregular variations in the weather.

The Air Force Cambridge Research Laboratories of the Air Materiel Command has sponsored investigations of this subject at the Harvard College Observatory during the past three years. Because we are now closing the investigations, at least temporarily, a rather brief statement of the present status of the problem seems particularly desirable at this time. Our work at Harvard, which has been reported in technical detail elsewhere[1], has an important bearing on the general picture.

Investigations of solar-weather relationships suffer from our lack of understanding of atmospheric processes. At the present time meteorologists do not have the knowledge of these processes that would be necessary, for example, to compute the effect on the atmosphere of any given change in solar energy. This state of affairs necessitates statistical and empirical analyses. However, the observational data necessary to conduct these analyses are also unsatisfactory. Among solar data, only the sunspot record extends back in time more than ten or fifteen years, and sunspots are correlated only in a very general way with solar energy variability. A satisfactory network of surface meteorological data is available only for the Northern Hemisphere, and there only for, at most, the last fifty years. Upper-air data are almost completely lacking before 1940. These facts help to explain the difficulties involved in studies of this type.

Nevertheless, the studies of recent years have drawn more and more meteorologists to the rather reluctant conclusion that solar variability, particularly in the ultraviolet part of the spectrum, may be an important contributing cause of vagaries in the weather.

2. Solar Variability and Its Indicators

Of the energy that leaves the sun, only that at certain wave lengths reaches the earth's surface. The energy that is available for surface measurement falls in the visible and infrared parts of the spectrum. The energy in the ultraviolet part of the spectrum, at wave lengths less than 3000 A, is almost entirely absorbed by nitrogen, oxygen, and ozone in the earth's upper atmosphere.

For about forty years, the Smithsonian Institution has conducted routine measurements of the intensity of the solar energy that can be measured at the earth's surface. Even this energy is partially absorbed by the atmosphere, so that its intensity at the surface is less than that originally reaching the top of the atmosphere. Complex corrections must be made to take into account the somewhat variable effect of the atmosphere, and uncertainties in these corrections limit the precision of the final determination of the energy leaving the sun. These determinations indicate only very small variability in solar output, variations of the order of magnitude of 1 percent of the total energy measured. Many scientists still feel that these suspected variations may result from uncertainties in the reduction of the observations.

On the other hand, there is indirect but satisfactory proof of important solar variability in the ultraviolet part of the spectrum. Variations in the earth's magnetic field and in the degree of ionization of the upper atmosphere indicate that the ultraviolet energy absorbed at those levels is variable. Observations of aurorae and the light of the night sky indicate similar variations in energy or in the number of fast-moving particles reaching the upper atmosphere from the sun. These phenomena are correlated in a general way, that is, in terms of monthly or annual means, with the sunspot number. However there is no definite one-to-one connection between these phenomena and individual groups of sunspots. Small variations in hydrogen emission observable in the visible part of the spectrum lead theoretically to an assumption of much larger variations in the ultraviolet. These variations accompany violent explosions on the sun called solar flares.

The sunspot number, because it is generally correlated with some upper-atmospheric parameters and because it has been observed for a relatively long time, is often used as an indicator of solar variability. It is not satisfactory, however, except as a symptom of the variability. Some more refined measure is needed to indicate, for example, daily fluctuations in solar energy.

No other solar parameter is available for any great period of time. Some investigators have turned, therefore, to the use of upper-atmospheric parameters as indicators of the solar variability. Some of these parameters have a record as old as that of satisfactory weather data.

3. Meteorological Variations

There most certainly are irregular variations in the weather, variations of great amplitude that are superimposed upon the seasonal variations. Everyone is familiar, of course, with the day-to-day weather changes associated with the movements of air masses, fronts, and pressure systems. At the other extreme of the time-scale, the geological record clearly indicates at least three glacial epochs, each of about 50 million years duration, separated by exceptionally warm and dry periods lasting perhaps 250 million years. The accepted practice among geologists and meteorologists has been to attribute the long-period changes to factors outside the mechanics of the earth's circulation, for example, to variable solar output, to variations in the earth's orbital elements, or to a variable topography of the earth's surface. On the other hand, the day-to-day changes have been generally assumed to be wholly explainable in terms of the circulation itself.

Willett has recently advanced a new philosophy of weather changes. He has called attention to the existence of other climatic fluctuations, fluctuations intermediate in amplitude and duration between the ice ages and the daily changes and, indeed, forming an essentially continuous spectrum between the two extremes. Geological evidence now shows that the last ice age, and, by implication, the others, was marked by successive advances and retreats of the glaciers, called stages. Each stage is distinguished by substages that repeat the same cycle but with smaller amplitude. Since the retreat of the last glacier, about 6000 B.C., world climate has undergone a similar cycle. During the Climatic Optimum, from about 5000 B.C. to 2000 B.C., world climate approached the optimum conditions of an interglacial period. Conditions then worsened during the Sub-Atlantic or "Peat-Bog"

period between 1500 B.C. and about 500 A.D. Since that period similar cycles, of still smaller amplitude and duration, are suspected from the scanty records available. During the past 80 years, shrinkage of glaciers and warming-up in high latitudes has been the rule. Average weather conditions for a season, a month, or a week often show striking differences from the "normal" seasonal values. Willett feels that all these climatic fluctuations result from the relative persistence, during the proper length of time, of circulation patterns that occur in our weather today.

Willett's penetrating analysis raises vital questions. Where in this almost continuous spectrum of weather changes can one draw a line to separate externally-caused changes from internally-caused changes? What common cause could lead to the persistence of a certain weather pattern over a few weeks, a few centuries, or a few million years? Many of us feel that there is no place to draw the line, that we must look for a common cause, and that this cause is most likely solar variability. This does not mean that we expect the intensity of the solar ultraviolet energy at a given time to be the sole criterion that determines a subsequent weather pattern. We certainly feel that an existing weather pattern has within itself a powerful impetus for a subsequent development. However, we feel that the ultraviolet intensity and its resulting upper-atmospheric conditions may very well furnish physical effects that would tend to guide the atmosphere into a definite pattern, effects that would, during moments of atmospheric "hesitation", have an important effect on subsequent developments.

These considerations prove nothing. They do, however, furnish us with a plausible justification for searching the solar and the meteorological records for proofs of the suspected connection. The difficulties of this search are enormous. The lack of adequate theory and observational material discussed in the introduction, together with the probable indirectness of any connection, have led to a rather confused state of affairs. Statistical studies have obtained controversial results, results accepted by some as proof of the suspected correlation but rejected by others as not statistically significant.

4. Previous Statistical Studies of Solar-Weather Changes

We have no intention in this brief discussion of attempting to mention all statistical solar-weather studies. That would be a monumental task. On the other hand, we do hope to illustrate

by a few examples the types of investigations that have been undertaken and the nature of the results obtained.

(a) Correlations of annual means of sunspot number and weather parameters.

The first type of investigation suitable for discussion here involves the computations of linear correlation coefficients between annual mean values of sunspot number and annual mean values of various meteorological parameters. This procedure involves a simple statistical approach and furnishes a useful background for other studies. Early in the history of solar-weather studies, Köppen[2] and Walker[3, 4] carried out investigations of this sort.

Walker's work is illustrative of the results obtained. Correlating the annual mean value of sunspot number with the annual mean value of surface pressure, temperature, or precipitation for each of a network of stations, he found no strikingly significant correlation coefficients. For stations near the equator, however, he found consistently negative coefficients between sunspot number and temperature, and between sunspot number and pressure. These coefficients were generally between —0.2 and —0.5 in magnitude, depending on the particular station involved. Thus, they are too small to be useful for forecasting but large enough to indicate probable statistical significance.

(b) Other studies relating sunspot number to weather parameters.

The simple statistical technique of Walker left room for many refinements. The use of annual rather than seasonal means, the use of the linear-correlation technique, lack of consideration of the initial state of the atmosphere, all could conceal important relationships. Many studies have attempted to consider these factors.

The investigation carried out by Hänzlik illustrates many of these other attempts. Hänzlik[5] compared the average pressure for the three years centered at a sunspot minimum with the average pressure for the three years centered at the following sunspot maximum. For about a hundred years, until the recent sunspot cycle, sunspot maxima have alternated between maxima with large values of sunspot number (called "major" maxima) and maxima with relatively small values of sunspot number (called "minor" maxima). From minimum to a major maximum Hänzlik found rising pressure in high latitudes, falling pressure in middle latitudes. On the other hand, from minimum to a minor maximum, he found the reverse pattern, namely, falling pressure in high latitudes, rising pressure in middle

latitudes. Furthermore, he found that these patterns were particularly accentuated during the winter season.

Clayton[6], Willett[7], and Wexler[8] have carried out similar studies with somewhat similar results. There is a question whether the results are statistically significant, that is, whether they illustrate an actual effect of changing sunspot number or whether they occurred simply by chance.

Similarly, Tannehill has constructed many graphs that illustrate rather impressive parallelisms between the sunspot variation and various meteorological parameters. Here again, adequate tests of the statistical significance of the relationships are lacking.

(c) Short-period solar variations and meteorological fluctuations.

Some studies have attempted to detect meteorological fluctuations caused within a few days by solar variations lasting only a few hours or a few days. For this type of analysis, the sunspot number is probably not a good indicator of solar emission, as mentioned above. Various other parameters have been used.

In a long series of studies Abbot[9] has tested the effect of above-normal or below-normal daily values of the solar constant, as measured by the Smithsonian Institution. His results are particularly controversial, because even the reality of the basic solar fluctuations has been questioned. Moreover, his results apply mainly to temperature or precipitation at given stations and do not lend themselves to simple interpretation in terms of large-scale weather patterns.

In a recent paper, B. and G. Duell[10] have given the average surface pressure fluctuations at some northwest European stations during the few days following days of high magnetic character figure, low magnetic character figure, and the occurrence of solar flares. These initial upper-atmospheric conditions presumably indicate, respectively, an impingement on the upper atmosphere of a large number of charged particles from the sun, a notable absence of such particles, and the arrival of an intense outburst of ultraviolet radiation from the sun. Studying only the winter months of years of low sunspot activity, the Duells found an average pressure fall two to four days after magnetically disturbed days, an average pressure rise two to four days after magnetically quiet days. Four to six days after a solar flare, for all seasons, they found a pressure rise.

The Duells made several efforts to test their data for statistical significance. They divided the magnetic data into odd and even

years and found similar results for each set of data separately. They divided the solar-flare data into summer and winter months and found similar patterns for both sets of data, but with greater amplitude in the winter than in the summer. More than most investigators, they seem to have showed the statistical significance of their results. However, even in their case a quantitative expression of this significance is lacking.

5. Studies at the Harvard College Observatory

Considering the background of studies outlined above, we at the Observatory felt that our optimum contribution to the question would be a careful study of the statistical significance of any results that we might obtain. Moreover, we were impressed by the Duells' work, not only because it seemed more likely to be significant than many other studies but also because the approach to the problem through day-to-day pressure changes was attractive. Any relationship that shows up in terms of seasonal or annual averages must have its root in terms of these daily changes, because the former represent the net effect of the latter.

Accordingly, we outlined a study to apply the Duells' techniques to as many locations as possible. Use of punch-cards made possible the computation of average pressure for the ten days following geomagnetically disturbed and geomagnetically quiet days at the intersection of every longitude circle divisible by ten and every parallel of latitude divisible by five between 30° and 70° N.

At nearly every one of these locations, a phenomenon similar to that reported by the Duells showed up clearly. The average change of pressure following disturbed days was in the opposite direction of that following quiet days at the same location. If the pressure rose after disturbed days, it almost invariably fell after quiet days, and vice versa.

In line with our determination to subject any results to careful statistical scrutiny, we obtained a quantitative measure of this tendency. For each location, we computed the over-all average pressure, the average of all the points on the disturbed-day curve and all those on the quiet-day curve. Then we counted the number of locations for which the curves were on opposite sides of this average value (that is, one curve above and the other below) for the day of opposite geomagnetic conditions, the first day following, the second day following, etc. Table 1 shows, for each of the eleven days in the period studied, the percentage

of locations where one curve was above and the other below the average.

TABLE 1

No. of days after anomalous geomagnetic conditions	0	1	2	3	4	5	6	7	8	9	10
Per cent of locations with one curve above average, the other below	57	57	69	67	68	75	73	73	71	62	53

A careful analysis of serial correlations in the original pressure data revealed that one should expect a certain amount of negative correlation between the disturbed-day curve and the quiet-day curve, even in the absence of a solar-weather effect. In terms of the parameter that we have chosen, that given in Table 1, this effect should cause the curves to be on opposite sides of the average at no more than 60 per cent of the locations. Note that on the day of disturbed or quiet geomagnetic conditions and on the first, ninth, and tenth days after, the results listed in Table 1 are in satisfactory agreement with this expected value. However, on the second through the eighth following days the correlation is much greater than this figure. Its average value during this period is 71 per cent. The clear implication of this work is that particularly disturbed geomagnetic conditions and particularly quiet geomagnetic conditions have opposite effects on the surface pressure two to eight days later.

We have investigated whether these results might reasonably have occurred by chance. If we repeated this study a very great number of times with different samples of the same size, and if there were no relationship between geomagnetic conditions and surface pressure, the correlations for all the samples would not be exactly the same. In fact, we should expect them to form some sort of a frequency distribution with a mean value of about 60 per cent and a certain standard deviation. This standard deviation turns out to be about 1.7 per cent, so that the value of 71 per cent (which we obtained for the second through eighth following days) would be over six standard deviations from the mean on the frequency curve. Statistically, this result would be very improbable by pure chance, so we conclude that the result in all likelihood does imply a connection between geomagnetic conditions and surface pressure.

What of the signs of the pressure changes? These signs vary from point to point on the earth's surface. Because the *difference*

between the disturbed-day curve and the quiet-day curve seems to be the statistically significant parameter, we have chosen to study its geographical distribution. At 60° N and 70° N, the difference is positive at nearly all longitudes on the second through the eighth days. No such consistency is evident for the beginning and end of the period. Similarly, for the second through the sixth days, the difference at 40° N is negative at nearly all longitudes, but no such consistency holds for the rest of the period. Note that this distribution of pressure changes is markedly in the direction of a higher zonal index after disturbed days than after quiet days. The difference in zonal index is about 2 mb on the fourth and sixth following days.

6. Future Development of the Studies

What have we learned from the studies discussed above?

In the first place, we have learned that these studies must go on. While the details of solar effects on the weather are still obscure, the existence of such effects is clearly indicated by several studies. Proof of their existence satisfactory to even the most confirmed doubter has been and will be difficult to obtain, from the very nature of the necessary statistical analyses. But meteorologists must continue to investigate the subject in view of the probabilities involved.

Some requirements for future investigations are also clear. The experience of past studies shows that there is no simple and clear-cut correlation to be found. Such factors as season, phase of the solar cycle, type of solar disturbance, and initial state of the atmosphere must be considered. Furthermore, the investigator must expect that other factors than the state of solar disturbance, factors depending on the mechanics of the general circulation, will turn out to be more important usually in determining the future weather.

One of the most basic needs for future studies is an expanded and accelerated program of solar research. This program must include routine application of existing observational techniques, development of new observational techniques, and theoretical studies of solar physics. The only solar parameter now available for statistical studies is the relative sunspot number. This parameter does not, as pointed out earlier, give the desired information about the precise physical state of the sun at any time. Other solar observational programs, such as flare patrols and coronagraph observations, will undoubtedly be of great impor-

tance. These programs must include mutually consistent observations at more than one station to eliminate gaps in the data resulting from bad weather in a given locality. Thus, more operating coronagraphs and flare detectors are needed for long-term use. Further rocket observations can gain new information about solar variability in the ultraviolet, its degree and spectral distribution. As great as is the need for more observations, no conceivable observational program can obviate the need for a greatly expanded theoretical attack. An understanding of solar physics is essential. Such an understanding not only would aid in the efficient use of current observations but also might provide for interpretation of past sunspot records and for prediction of future solar conditions.

Present knowledge is inadequate to frame any hypothesis as to the nature of the effect of solar variability on the earth's atmosphere. Yet, we can take note of the tendency for increasing solar activity to result in pressure rises at increasingly higher latitudes. Hänzlik and, particularly, Clayton have pointed this out in terms of sunspot maxima, with pressure rises occurring at minor maxima in middle latitudes, at major maxima in high latitudes. Our results show higher pressures at 60° and 70° N after geomagnetically disturbed days than after quiet days.

Fifteen years ago, the study of solar-weather relationships was considered by many to be an undignified pursuit for a meteorologist. Today it is a respected field for further investigation. Fifteen years from now, it may well be a crucial part of long-range forecasting studies.

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WILL OUR SUN EVER EXPLODE?

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It is a well-established fact that energy production in stars is due to the thermonuclear transformation of hydrogen into helium. Since hydrogen forms about one-half of normal stellar material, the rate of its consumption, i.e., the luminosity of the star, determines the stellar life span; in the case of our sun it can be calculated to be about fifty thousand million years, which is very long as compared with the estimated age of the stellar universe. Since, however, stellar luminosity (hydrogen consumption) increases very fast with stellar mass (hydrogen content), life spans of brighter stars are considerably shorter. Thus stars of about zero absolute magnitude would run through their hydrogen evolution in a few thousand million years, i.e., in a period of time which is generally accepted to represent the age of our universe. And, indeed, we notice that the stars of zero absolute magnitude seem to represent a demarkation line in the stellar population of our galaxy. Thus the main sequence of the Russell-Hertzsprung diagram shows a noticeable discontinuity at that particular point. The brighter stars are very scarce in space and are in a state of rapid axial rotation; the fainter stars are very abundant and hardly rotate at all. Also, within stellar population II, as defined by Baade, (the regions of the galaxy where no interstellar material is present) the upper part of the main sequence is completely absent. All this suggests that zero absolute magnitude divides the main sequence into the older (lower) part containing the original stock of stars formed almost simultaneously a few thousand million years ago, and the younger (upper) part consisting of stars formed by condensation processes at various more recent epochs. We may also notice that zero absolute magnitude serves as an apex from which the main sequence of stars branches out into "swollen-up" stellar types such as pulsating variables and red giants in general, and "shrunken" stellar types which include Wolf-Rayet stars, nuclei of planetary nebula, white dwarfs, and various types of exploding stars (U-Geminorum, recurrent novae, ordinary novae and supernovae). It is difficult to escape the impression that *stars deviating from the main sequence are those which run out of their original hydrogen supply, a situation which*

forces them to go through "unusual" final stages of their evolutionary life. One would expect, in fact, that all these stars have comparable masses (at least at the stage when they leave the main sequence) of the order of magnitude of three sun masses and about the same total life span of a few thousand million years. This conclusion finds support in the *Kukarkin-Parenago* relation according to which the intensity of periodic stellar explosions (U-Geminorum stars, and recurrent novae) is directly proportional to the period between explosions. This relation, indicating a constant total rate of energy production, would be difficult to understand for stars of different masses, and consequently, different central temperatures.

If we look at this problem from the point of view of possible stellar models, we find that an aging star should be expected to develop a so-called "shell-source" of nuclear energy. In fact, when all the material in *Cowling's* convective zone supplying fresh fuel for nuclear reactions in the center is completely dehydrogenized, the reaction would transfer into a spherical layer between the isothermal helium core, and the radiative hydrogen-rich envelope. The properties of such shell models have been studied by many authors with rather interesting results. It has been found that an attempt to fit a small isothermal core into a radiative envelope (with the temperature and pressure continuous at the interface) results generally in several possible solutions. One of these gives a star of extremely large radius which can be considered as a tentative model of a red giant. The other two solutions are rather similar between themselves corresponding to stars of more or less normal size. However, when the fraction of the stellar mass in the core increases (due to the progressive nuclear reaction) these two solutions disappear, leaving the evolving star in an odd position of "not knowing what to do". The situation is represented schematically in Fig. 1 showing three intersections (1, 2, 3) for smaller cores and only one intersection (3′) for larger cores. The disappearance of two intersections for larger cores means physically that *it is no longer possible to fulfill the continuity conditions both for temperature and pressure.* If we "force" a solution for some interface-radius a, we find an *inversion of pressure* and the star will start to collapse. We can, of course, stabilize the model by raising the temperature (and hence the pressure) at all points of the core, but this will *produce a non-stationary thermal state* and lead to gradual heating of the inner layers of the hydrogen-containing envelope. The situation is rather

analogous to that in an ordinary electric bell where the clapper can neither stay at the electromagnet nor at the electric contact. It is difficult to predict the behavior of the model without rather elaborate hydrodynamical calculations, but it is apparent that at this point of evolution the static model must go over into some kind of *periodic motion*. When the stability conditions are

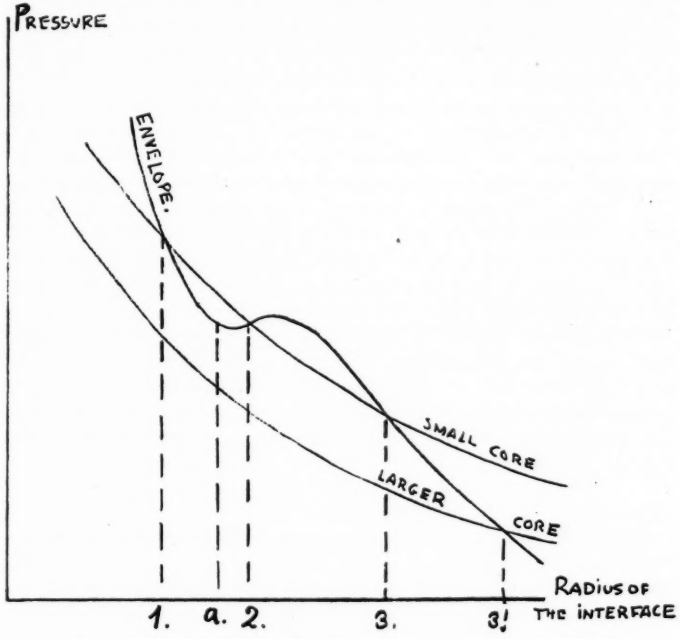

FIG. 1

The dependence between the pressure at the interface and its radius for the base of the radiative envelope and the surfaces of two isothermal cores. (Schematic drawing)

just exceeded we would expect short period motion with small amplitudes. As the core grows, both period and amplitude would be expected to become larger and larger. Thus we have here a picture which may be useful for the explanation of the *Kukarkin-Parenago* relation *if we consider different U-Geminorum stars as successive evolutionary stages of a single stellar mass.*

It may, indeed, easily happen that the above described "oscillations" will result in periodic convectional instabilities. In this case a fast mixing of cool hydrogen from the envelope with hot helium from the core *will result in instantaneous nuclear explosions* of the star. The possibility is also present that similar instabilities may develop in "swollen-up" solutions of the shell-model. If the resulting central explosions are comparatively weak, they will not show through the thick body of the star and may act as a *"Buzzer" mechanism for maintaining regular stellar pulsations.*

It is too early to say whether or not the above views will lead to a correct explanation of the dynamical states of aging stars. The study of the hydrodynamical equations involved in the problem is extremely difficult and can be done only by means of modern electronic computers. Work in this direction is now being done by the author and his colleagues: A. Carson, G. Keller, C. Longmire, N. Metropolis, L. Peck and R. Richtmeyer with the hope of having solutions run on a new electronic computer ("Maniac") under construction at the Los Alamos Scientific Laboratory. When the Maniac starts "thinking" he will certainly turn out the answer to that problem in no time. Then, and only then, will we really know how violent the explosions of smaller stars can be. Then, and only then, we will know whether the explosion of our Sun will warm up, melt, or evaporate our Earth.

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PART 3

SURVEY OF ENERGY SOURCES, NEEDS AND UTILIZATION

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WORLD'S ENERGY SUPPLIES AND THEIR UTILIZATION

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1. CURRENT AND FOSSIL ENERGY SOURCES

With few minor exceptions such as nuclear power and tide energy, mankind's energy supplies are derived from the radiant energy of the sun. These supplies come under two headings: energy originating in the radiation flux currently reaching the earth, and solar energy stored millions of years ago in fossil carbon and the free oxygen of the atmosphere. Heat and power derived from products of current photosynthesis, and power derived from falling water are the two most important items in the "recurrent" energy budget; while heat and power derived from the combustion of coal, oil and natural gas are the major items of the "non-recurrent" income. Minor contributions to the recurrent income are provided by wind energy, energy derivable from the temperature gradient in the sea, and energy produced by solar heaters and solar power plants of various design.

In 1937, according to a study sponsored by the U. S. State Department,[1] mankind consumed 7.0×10^{12} kilowatt-hours of energy from recurrent sources — 5.0×10^{12} kilowatt-hours of these in the form of food energy for man and feed energy for animals — and 16.2×10^{12} kilowatt-hours from the irreplaceable storehouse, all of it for domestic and industrial heating and power production. In other words, man derives his and his domesticated animals' sustenance entirely from the current supply of solar energy, but covers, at present, almost 90 per cent of the energy needs of civilization from solar energy stores bequeathed by past ages.

2. PHOTOSYNTHESIS AS MAIN SOURCE OF ENERGY

Ninety-nine per cent of both the replaceable and the irreplaceable energy supplies used by man comes to us through a single channel—photosynthesis of plants. In 1845, three years after J. Robert Mayer had first proclaimed the law of conservation of energy, he wrote in an essay entitled[2] *The Organic Motion in Its Relation to Metabolism*:

Die Natur hat sich die Aufgabe gestellt, das der Erde zustroemende Licht im Fluge zu erhaschen und die beweglichste aller Kraefte, in starre Form umgewandelt, aufzuspeichern. Zur Erreichung dieses Zweckes hat sie die Erdkruste mit Organismen ueberzogen, welche lebend das Sonnenlicht in sich aufnehmen und unter Verwendung dieser Kraft eine fortlaufende Summe chemischer Differenz erzeugen. Diese Organismen sind die Pflanzen; die Pflanzenwelt bildet ein Reservoir in welchem die fluechtigen Sonnenstrahlen fixiert und zur Nutzniessung geschickt niedergelegt werden; eine oekonomische Fuersorge an welche die physische Existenz des Menschengeschlechtes unzertrennlich geknuepft ist.

In 1937, mankind consumed 16.2×10^{12} kilowatt-hours of energy from prehistoric photosynthesis, and 6.8×10^{12} kilowatt-hours from current photosynthesis. The only significant supplement to photosynthetic energy (accounting for the discrepancy between the last figure and the 7.0×10^{12} kilowatt-hours quoted in Section 1 as the total energy amount derived in 1937 from recurrent sources) is the approximately 0.2×10^{12} kilowatt-hours obtained in that year from the utilization of the energy of falling water — an item which, too, is of solar, but not of vegetable origin.

3. Total Yield of Photosynthesis on Earth

Since photosynthesis by plants constitutes the main path through which solar radiation energy becomes available to man, we will now consider its material balance and energy accounting more closely.

The material balance can be expressed in terms of tons of carbon that pass from inorganic into organic combination every year. This amount can be estimated from average crop production per unit area of different types of vegetation — forests, meadows, fields and the phytoplankton in the sea.

The results of such an estimate[3] are shown in Table 1.

Table 1

Total Photosynthetic Production on Earth

	Sea	*Land*	*Total*
Area in million sq. km.	360	150	510
Tons carbon fixed per yr.	15.5×10^{10}	1.9×10^{10}	17.4×10^{10}

One relation, not generally known, that strikes one in Table 1 is the predominance of the aquatic plants (i.e., of the microscopic, free-swimming phytoplankton) as contributors to the total photosynthetic production on earth. The contribution of the benthos — the ground-bound algal vegetation of the continental ledge — to marine photosynthesis is quite small in proportion.

The fact that most of the algae of the phytoplankton are brown (rather than green) deflates the importance often attached to the adjective "green" in "green plants" as *the* accumulators of solar energy on earth. True, the green pigment chlorophyll is present in brown, red and blue-green algae as well as in the green ones; but recent investigations[4] have confirmed the view — first expressed by Engelmann seventy years ago — that light absorbed by the yellow, red or blue pigments contained in photosynthesizing plant cells contributes to the photosynthesis about as effectively as the light absorbed by the green pigment chlorophyll. If Haxo and Blinks[5] are right, the red pigments in some red algae might be even more efficient in photosynthesis than the green ones.

If we recall that sunlight becomes greenish after passing through a few meters of sea water, we realize that the green light, absorbed predominantly by the principal carotenoid pigment of diatoms, fucoxanthol (the pigment which causes their brown color) must constitute a very considerable fraction of all the solar energy utilized by plants.

4. Reserves of Fossil Products of Photosynthesis

It is of interest to compare the yearly synthesis of organic carbon, estimated in Table 1, with the known resources of fossil organic carbon on earth. The latter, according to 1937 estimates,[1] amounts to about 500 x 10^{10} tons of coal (with oil, peat and natural gas adding qualitatively important, but quantitatively insignificant amounts), or approximately 450 x 10^{10} tons of carbon. This is equivalent to the photosynthetic production of all plants on earth in about 25 years at the presently prevailing rate. However, since coal deposits that might exist under the floor of the oceans are not included in the estimate, it would be fairer to compare the known coal reserves with the production of organic carbon compounds by land plants only; the latter would require about 250 years to synthesize the amount of organic carbon contained in all presently known coal deposits. This gives us an idea of how small must have been the fraction

of the total photosynthetic production that underwent carbonization, even in the forests of the carboniferous era.

Since the total yearly coal consumption has been estimated in 1937 at about 0.1×10^{10} tons, it appears that at the then prevailing rate of consumption, the presently known coal reserves would last for about 5000 years and also that every year man uses up in the form of fossil fuel, the equivalent of 5 per cent of the yearly photosynthetic production of all land plants.

5. Total Energy Conversion by Photosynthesis

The estimate of total carbon conversion to organic matter by photosynthesis can be complemented by a largely independent estimate of the amount of solar energy converted into chemical energy. The calculation, which although very crude should involve no errors in order of magnitude, goes as follows:

1. Total solar radiation impinging yearly on earth's outer atmosphere: 1×10^{18} kilowatt-hours
2. About 40 per cent of it reaches sea level (the rest is absorbed or scattered by the atmosphere): 4×10^{17} kilowatt-hours
3. 50 per cent has $\lambda < 700\ \mu$, and is therefore unsuitable for photosynthesis, leaving: 2×10^{17} kilowatt-hours
4. About 20 per cent is reflected, or absorbed by ice caps, deserts, or snow in winter; leaving: 1.5×10^{17} kilowatt-hours
5. An average of 20 per cent of visible radiation, falling on the surface of the sea, or on vegetation-covered land, is reflected, or absorbed by non-living material; leaving for the absorption by plant pigments: 1.2×10^{17} kilowatt-hours

Now comes the widest jump: from the energy *absorbed* by plant pigments, to the energy *stored* by plants in the form of synthesized organic compounds. The best we can do here is to use the results of several large-scale determinations of the amount of

organic matter produced over an extended period of time, by forests, grass plots and cultivated fields, and in the ocean. These investigations indicated, for land plants, conversion yields of the order of 1 to 2 per cent; widely varying, but—on the average—slightly higher yields were found in the ocean.

Taking into account that in the sea vegetation continues the year round, it seems fair to use 1.5 per cent as the overall average for sea and land, winter and summer. This brings us to a figure of 1.8×10^{15} kilowatt-hours for annually stored solar energy. Assuming that the photosynthesized carbon compounds have an average heat of combustion of 10^{10} calories (1.1×10^{4} kilowatt-hours) per ton carbon contained in them (which means that they have, roughly, the reduction level of carbohydrates), we calculate that the above estimated annual energy conversion yield requires the fixation of $1.8 \times 10^{15} / 1.1 \times 10^{4} = 1.6 \times 10^{11}$ tons of carbon, in good agreement with the value (1.8×10^{11} tons) derived above from crop estimates.

The storage of 1.7×10^{15} kilowatt-hours per annum by plant photosynthesis can be compared with the previously mentioned figure of 2.3×10^{13} kilowatt-hours per annum for the total energy consumption by mankind in 1937. This comparison shows that about 1 per cent of the total photosynthetic energy on earth, or about 10 per cent of total photosynthetic energy produced on land, would be enough to cover all our present-day energy requirements.

6. Fate of Energy Stored by Photosynthesis

Only a small proportion of photosynthetically produced organic compounds and of the potential chemical energy stored in them is (or, for that matter, ever can be) utilized for food, fuel or power production. In the first place as much as 90 per cent of the total is generated in the sea, where only an infinitesimally small fraction finds its way via the plankton into fish caught and consumed by men (or by animals useful to man such as whales). The total weight of fish and shell fish caught every year has been estimated as 1.8×10^{7} tons—about 50 kilograms per square kilometer of the surface of the ocean—containing about 3×10^{6} tons of organic carbon, or 1 part out of 50,000 parts of carbon photosynthesized in the ocean.

Of the approximately 1.7×10^{10} tons of organic carbon synthesized on land, as much as 1 per cent is utilized for human food (1.7×10^{15} kilocalories per year, corresponding to about

2,100 kilocalories per day per capita, for a total population of 2.2 billion).

Animal feed accounts for another 1.5 per cent and fuel wood, used in part for industrial purposes, but mostly for domestic heat and cooking, also for slightly more than 1 per cent. Together, these three items were estimated in 1937 to account for an equivalent of 7×10^{12} kilowatt-hours of energy — 3.9 per cent of the chemical energy stored yearly by land plants.

What happens to the remaining 96 per cent of the synthesized organic matter? About 15 to 20 per cent must be deducted, since it is used up for the *plants' own respiration;* the fate of the remainder, perhaps as much as 80 per cent of the total, is to be destroyed in the rotting of plants and plant organs, leaves shed by deciduous trees, stalks and roots of annual plants, and wood of dead trees or fallen limbs. The conversion of this enormous weight of organic material, mostly cellulose, back into carbon dioxide and water is catalyzed by bacteria, which thus provide the main avenue by which the carbon cycle is completed on land. Plant respiration plays only a relatively minor, and animal respiration a practically insignificant role in returning into the air the carbon dioxide fixed by land plants.

The situation is different in the sea, where the *zooplankton* plays quantitatively a much more important role than its counterpart of land, the land animals. It is generally assumed that the zooplankton is maintained in dynamic equilibrium with the phytoplankton — meaning that it multiplies until it can consume all or almost all of the organic matter synthesized by the phytoplankton. A large proportion of the organic matter synthesized by phytoplankton is destroyed by bacteria, either before or after it has found its way into the zooplankton; but this part is probably not as all-important as on land, while the part returned into inorganic form *via* animal respiration is correspondingly larger.

The carbon cycle in the sea is completed predominantly in suspension; in other words, the larger part of the organic material never settles to the bottom of the sea. Of the fraction of organic material that does drop to the sea bottom, the largest part must be re-oxidized there by bacteria; the fraction undergoing fossilization under the sea (or in landlocked waters or bogs) must be very small, since the annual turn-over of photosynthesis corresponds to the fixation of 0.2 per cent of all the carbon dioxide available in the atmosphere (as CO_2-gas) and in the ocean (as carbonate ions). An annual withdrawal of as little as one per

cent of the products of current photosynthesis by fossilization would deplete the carbon dioxide reserves of the air and of the sea in as short a time as 50,000 years.

7. Fate of Solar Energy Not Used for Photosynthesis

What is the fate of the 98 per cent of the visible, and 99 per cent of total, solar radiation reaching sea level but *not* converted into chemical energy by photosynthesis? A very large proportion of it, absorbed by both organic and inorganic constituents of sea water, is used to *evaporate water* from the oceans; this part has been estimated[6] as high as 40 per cent. On land most of the light energy absorbed by plants also is used for *transpiration*, i.e., water evaporation from leaves (although, under some conditions, almost as much energy may be reradiated by plants into space as is used for transpiration). The energy spent on transpiration of land plants has been estimated by some as up to a thousand times that used for photosynthesis. However, this seems exaggerated; if 1.5 per cent is an approximately correct estimate of the proportion of visible light energy taken up by land plants that is converted to chemical energy by photosynthesis, not more than 100 times this amount can be allotted to transpiration—even if one takes into consideration that infrared light not used for photosynthesis can contribute to transpiration. (Green plants do not absorb strongly in the near infrared, as is well known from infrared landscape photographs, in which green vegetation appears white.) Altogether it seems likely that 5 to 8 per cent of the total solar energy (comprising both visible and infrared) reaching sea level is used for the transpiration of green plants—in addition to the 40 per cent used for water evaporation from the oceans. This leaves about 50 per cent of this energy (mostly the infrared) unaccounted for; this energy must either be reflected by the earth's surface or absorbed by inorganic compounds of the hydrosphere and the lithosphere and converted into heat. Ultimately, of course, all the solar energy that reaches the earth, if not reflected, is converted into heat and reradiated into space as low-temperature heat radiation, the only distinction being in the channels (chemical energy, mechanical energy, electrical energy) through which some of the radiation energy passes before it is degraded to heat.

The 2×10^{17} kilowatt-hours (50 per cent of 4×10^{17}, see section 4) of radiation energy converted into the potential energy of water vapor every year are, of course, converted back into heat when vapor condenses in the clouds. The only energy of water

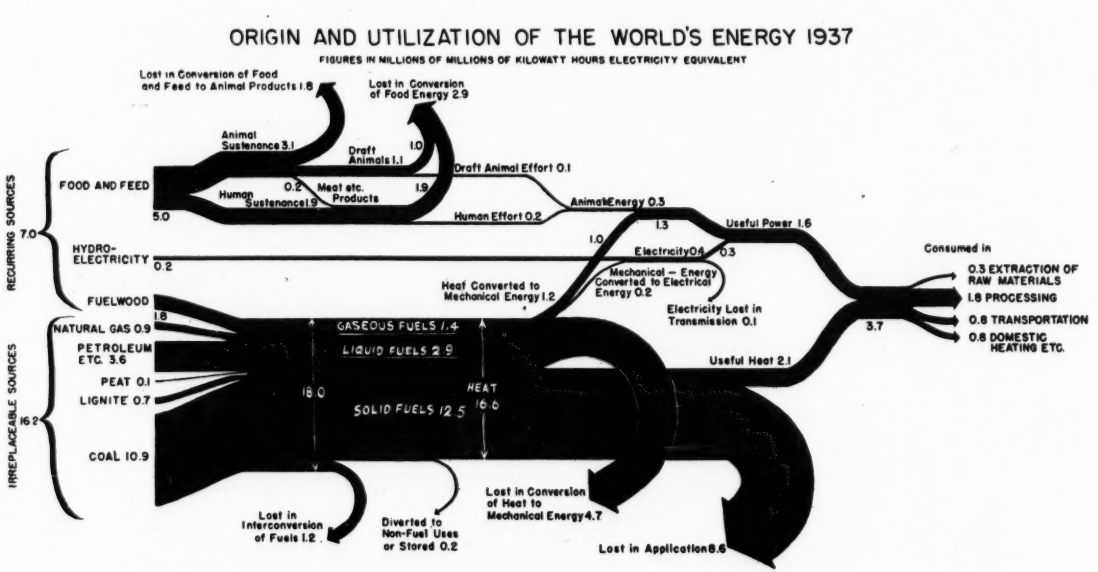

FIG. 1. Origin and Utilization of Energy in the World in 1937 (from "Energy Resources of the World"[1])

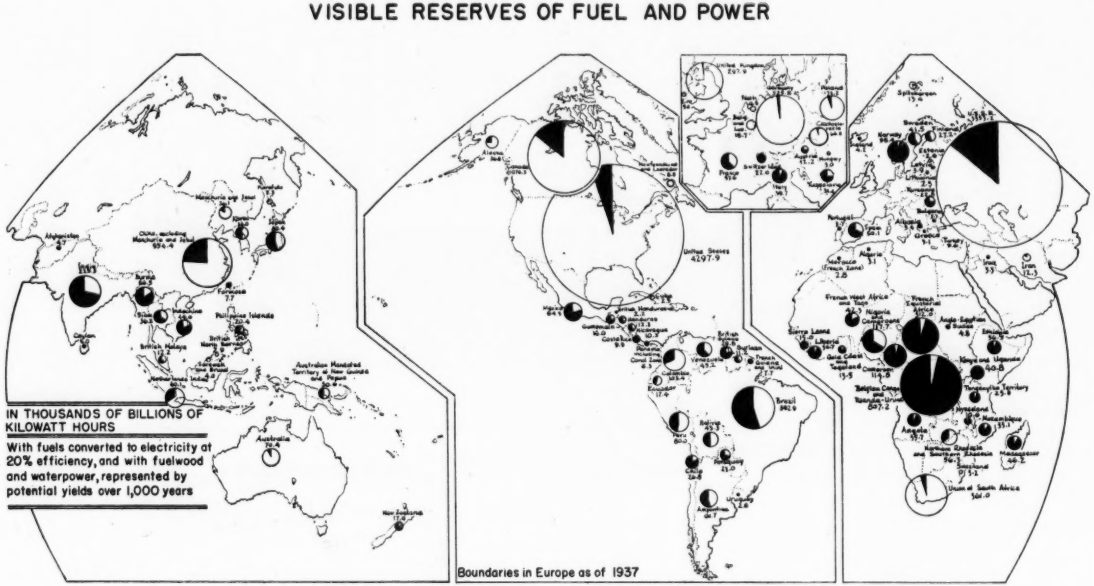
VISIBLE RESERVES OF FUEL AND POWER
IN THOUSANDS OF BILLIONS OF KILOWATT HOURS
With fuels converted to electricity at 20% efficiency, and with fuelwood and waterpower, represented by potential yields over 1,000 years
Boundaries in Europe as of 1937

FIG. 2. Resources of Fuel and Power by Countries in 1937
(from "Energy Resources of the World"[1])
White segments — Fossil Resources
Black segments — Water Power (Potential Yield in 1000 years)

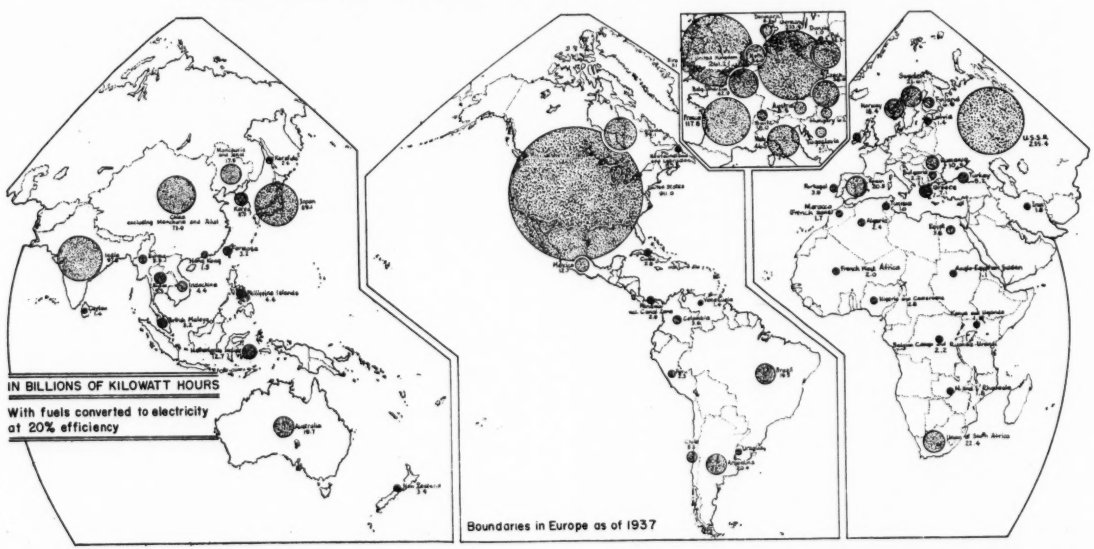
ENERGY CONSUMPTION FOR PRODUCTIVE PURPOSES IN 1937
IN BILLIONS OF KILOWATT HOURS
With fuels converted to electricity at 20% efficiency
Boundaries in Europe as of 1937

FIG. 3. Consumption of Energy for Productive Uses by Countries in 1937. (from "Energy Resources of the World"[1])
(See note on page 312)
"Productive uses" means that food and feed energy is not included, except for the small part which is utilized as "animate energy" in industry and agriculture. See reference 12 on page 312.

vapor that is at least partially utilizable is the potential energy—estimated as 4×10^{15} kilowatt-hours per year[6]—stored by lifting water vapor to the level where the clouds are formed. Most of this energy is lost through friction and impact of rain drops falling on the ocean or on land surface. Of the relatively small fraction of evaporated water condensed on hills, mountains or tablelands, and thus retaining substantial potential energy, only a small proportion finds its way into rivers suitable for hydroelectric development. We are thus not astonished to find that the total apparent *resources of water power* in the world have been estimated in 1937 as only 4×10^{12} kilowatt-hours per year.

Of these water power resources, as much as 4.3 per cent have been utilized for hydroelectric power in 1937 and the proportion is increasing rapidly, having reached 6.3 per cent by 1946.[1] Germany was making use of 59 per cent of its water power resources already in 1937; Switzerland, of 33 per cent. In North America, the coefficient of utilization was 22 per cent in 1937 and had risen to 39 per cent in 1946. On the other hand, less than 0.05 per cent of available water power had been utilized in 1937 in Africa, and only 0.7 per cent in South America.

8. Distribution of Energy Resources

Figure 1, taken from the same 1937 survey,[1] gives a graphic picture of the fate of the "recurrent" and "non-recurrent" items in the energy budget of mankind. It shows some relations of which many of us are not always aware. In the upper half, which depicts the fate of recurrent energy supplies, it is surprising to find that domestic *animal* sustenance consumes one half as much food energy as human sustenance (3.1×10^{12}) and that only a small trickle of this feed energy returns to man in the form of meat and other animal products (0.2×10^{12} kilowatt-hours), or of the mechanical effort of draft animals (0.1×10^{12} kilowatt-hours). The keeping of domestic animals thus appears a great waste even though most of the food used by animals is not fit for human consumption, and much of the land on which it is grown is unsuitable for growing economically useful crops.

The lower half of the figure, which depicts the fate of energy used for heat and power, also indicates tremendous losses. At the beginning, all this energy is chemical energy; and, since combustion of solid fuels increases entropy, the free energy available in them is even somewhat (although not significantly) larger than the total energy shown in Figure 1. However, practically all this

energy—except hydroelectric power—is converted into heat before it is used for the production of electricity or mechanic power, and this makes great losses in the subsequent reconversion of heat to mechanical or electrical energy thermodynamically inevitable. According to the figure, these losses amount to 4.7×10^{12} out of 5.9×10^{12} kilowatt-hours, or about 80 per cent.

A similar and much less justified loss of 80 per cent occurs also in the practical utilization of heat energy as such. According to Fig. 1, 8.6×10^{12} kilowatt-hours are wasted out of the 10.7×10^{12} kilowatt-hours used for this purpose. Altogether, out of 18.5×10^{12} kilowatt-hours of energy fed in on the left side of the flowsheet in Figure 1, only 3.7×10^{12} (or 20 per cent) emerge on the right side as sum total of actually utilized heat and power.

Figures 2 and 3 give a picture of the geographical distribution of energy resources over the different parts of the world and of the present rate of utilization of these resources. One striking fact illustrated by Fig. 2 is the almost exclusive concentration of fossil fuel resources in the Northern Hemisphere above 30° latitude. The only significant exception is South Africa, with sizable coal deposits. Water power resources are distributed somewhat more uniformly over the world; but of the large fuel-deficient areas (South America, Africa, South and South-East Asia), only two regions—the northern portion of South America and Central Africa—have large, unused water power resources. Central Africa in particular is the largest potential producer of hydroelectric power in the world. On the other hand the over-populated countries of Asia, such as India, China and the southern half of South America, are poor in both coal and water power.

The geographical distribution of energy *consumption* shows an even greater inequality in favor of the countries of the western world, including North America and Russia, well provided by nature with the wherewithals to develop an industrial civilization. However, these resources are nearing exhaustion in Great Britain, whose coal is getting scarce and which does not possess much water power. The unfairness of nature in distributing fossil fuels and water power over the globe is a very serious handicap to the plans of industrialization of South-East Asia and South America—plans on which all hopes of ultimate stabilization of the population of these areas and rise of their living standards are commonly based. Central Africa on the other hand, looms as a possible future center of industry, particularly if the problem of transmission of high voltage direct current over long distances would be satisfactorily solved.

9. Future of Nuclear Power

Being poor in both coal and water power, Asia and South America should be more eager than any other parts of the world for successful development of atomic power.

Whether nuclear energy will ever make a significant contribution to the energy budget of mankind is currently a matter of conjecture but the promise does not appear very bright. Even if one leaves aside military considerations (which call for stockpiling of all available nuclear explosives for possible use in case of war), two formidable questions remain without whose satisfactory solution no quantitatively significant atomic power industry appears feasible. (1) Will new, abundant high-grade deposits of uranium ore ever be discovered and if not, will the utilization of low-grade raw materials become economically justifiable; and (2) Will "breeding" of fissionable material in nuclear reactors become not only possible, but economical?

To cover the present world energy requirements, it would be sufficient to fission completely only 40 tons of uranium yearly. If fission is restricted to the isotope U^{235} and the latter is utilized completely, 5200 tons of uranium would be needed. Practically, of course, only a modest fraction of U^{235} can be utilized without breeding, and only a fraction of U^{238} with breeding. If breeding proves impossible the total apparent world resources of high-grade uranium ore would not suffice (according to pre-war estimates) to furnish a sizable proportion of world energy requirements for more than a few years. A few hundred tons of uranium metal may be obtainable yearly for a few decades from the presently exploited two deposits at Great Bear Lake in Canada and at Chinkolobwe in the Belgian Congo, until these are exhausted. With breeding, the same sources may provide enough uranium to last for perhaps a century; but, how expensive will breeding be, even if it proves technically possible? No new uranium ore deposits of comparable abundance have been discovered since 1945 outside the Iron Curtain;[7] i.e., in the larger part of the areas where such deposits could be expected to turn up according to geological analysis. Whether the Soviet explorers have been more lucky in discovering geological "freaks" of the type of the Chinkolobwe mines or the Eldorado mine in their parts of the continental shield has not been revealed, but frantic scraping of uranium crumbs from the long-abandoned mines of Saxony and Bohemia (and equally frantic agitation for the outlawing of atomic bombs), look like symptoms of great uranium scarcity in the Soviet domain.

Low-grade uranium "ores" (phosphates, shales, gold mine tailings) undoubtedly can be utilized if costs are no obstacle—as for military needs; but for industrial power or heat production nuclear energy at exorbitant price could not be tempting except, perhaps, under very special conditions, and nuclear fuel from low-grade materials is unlikely ever to become a cheap material. Power production costs will always be higher for atomic power than for conventional power plants because of radiation shielding, if for no other reason, while energy distribution costs will not be smaller. If material and production costs are high, what remains as a unique asset of nuclear energy is only its enormous concentration and consequent easy transportability, i.e., the possibility of carrying (or releasing) enormous amounts of energy in a very small volume. Except for some research purposes this is a purely military advantage. For military ends and military ends only, high concentration of energy is important not only in explosives, but also in propellants to operate submarines almost indefinitely without refueling and without a fresh supply of oxygen and to maintain planes flying for a long time over hostile territories.

Countries with abundant conventional energy supplies may never use nuclear energy in significant quantities except for military purposes, or as by-product of military production of nuclear explosives. Certain industries in power-deficient countries, such as South America or South-East Asia, might conceivably benefit by nuclear power despite its high cost, but who is going to provide them with nuclear fuel? As long as military considerations will remain valid, and that means as long as war will remain even a remote possibility, stockpiles of fissionable materials will be guarded by the major nations with more jealousy than their gold reserves.

Because of enormous "over-destruction" in the center of an atomic explosion, the waste of energy in atomic bombs is even greater than in conventional high-explosive bombs. The explosion of a single atomic bomb probably wastes as much energy as is used yearly by a country the size of Denmark! It is, therefore, unlikely that any sizable amount of nuclear explosives will be declared "surplus" even in times of apparently stable peace and released for export to countries deficient in non-atomic power sources—except, perhaps, under complete control of an organization of the type envisaged in international control schemes of the Acheson-Lilienthal type.

10. Improved Utilization of Conventional Energy Sources

The main hopes of mankind to achieve a better and more equitable supply of energy must at present be sought, not in the realm of nuclear physics, but in better utilization of conventional energy sources.

More complete utilization of water power may permit the industrialization of large presently backward areas, particularly parts of South America and much of Africa. For the parts of the world well endowed with coal, the most important aim seems to be to reduce its wastage by improving the thermodynamic efficiency of power production and, most of all, by increasing the efficiency of utilization of chemical energy in domestic and industrial heating. The development of high-temperature-resistant materials for turbines and other power plant equipment in the course of atomic power studies may well prove a most important contribution of these studies to the world power problem.

In areas of cheap electric energy, electric heat-pumping (refrigeration run in reverse) may prove to be more economical than coal burning, permitting mankind, for once, to put to its advantage the second law of thermodynamics, which rules that the energy needed to move a certain amount of heat from lower to higher temperature is smaller, the smaller the difference in temperature.

11. Direct Utilization of Sun Energy

The most universal hope for future improvement of energy supplies lies, however, in direct utilization of the current supply of solar energy—a supply that flows abundantly all over the world, including the regions poorest in coal and water power. Which of the presently discussed or actively investigated processes of solar energy utilization will finally become a major power and heat source is too early to predict. To show the wide range of possibilities, we will enumerate some of the contemplated projects:

(1) Improving drastically the performance of plants by *growing large masses of algae* in closed circulation systems, provided with ample supplies of air and carbon dioxide. Under natural conditions, the yield of photosynthesis of plants could not be much improved without hitting the "ceiling" imposed by the limited supply of carbon dioxide. If a medium fertilized with carbon dioxide is used, one can begin thinking of breeding algae capable of utilizing efficiently much higher light intensities

than those that "saturate" photosynthesis of presently known strains. If large masses of algae could be produced in this way, the dried product might prove to be utilizable as fuel, if not as animal feed—perhaps even as a supplement to human diet.[8]

(2) Utilization of the *temperature difference between surface water and deep water* in the ocean (George Claude). A pilot plant in West Africa, built by the French Government, plans to use the temperature gradient of 20° C between surface water (28° C) and water in 400 m depth (8° C), pumped to the surface, to operate a turbine. (Pre-war attempts by Claude in West India have ended in loss of the giant pipe while it was towed to the place where it was to be sunk into the ocean.)

(3) A project is being sponsored by Egypt to build a channel from the Mediterranean to the Quattara depression to produce hydroelectric power, relying on the sun to evaporate the water from the bottom of the depression.

(4) *Direct sun heating* of buildings in winter (or, possibly cooling by solar energy in summer!) as practiced in some parts of the United States and studied systematically by Hottel and Telkes[9] at the Massachusetts Institute of Technology.

(5) *Solar power plants,* based on concentration of solar heat on steam boilers—a favorite dream of inventors for many years past.

(6) *Conversion of light to electricity*—either directly (as in barrier-layer cells) or via chemical energy, as in photovoltaic or photogalvanic cells[10] or via heat, as in thermo-elements.[9]

(7) *Conversion of light to chemical energy,* in imitation and improvement of the performance of plants in photosynthesis. This is perhaps the most promising field. It seems incredible that a chemical system could not be compounded in which visible light would produce a chemical change, converting considerably more than 1.5 per cent of the incident light energy into potential chemical energy. Of course, the latter must be obtained in practically utilizable form—such as that of a mixture of hydrogen and oxygen, produced by photolysis of water. The true difficulty seems to lie, not so much in finding a photochemical reaction in which the desired conversion of energy actually takes place, as in stabilizing the products of the photochemical reaction, and preventing them from immediate recombination. The secret of photosynthesis is the way in which the plants manage to prevent

the unstable oxidation and reduction products formed by light from reacting back and separate them as molecular oxygen and relatively stable organic compounds. To a certain extent, similar reactions have already been achieved in isolated chloroplasts, and even in chlorophyll solutions.[11] Perhaps the secret of final success will be found in rapid adsorption or extraction of the unstable products of the primary photochemical process.

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[7] BRADLEY, W. H., *Bull. Atomic Scientists, 6,* 149 (1950).

[8] MEIER, R. L., this volume p. 196.

[9] HOTTEL, H. C., this volume p. 313.

[10] RABINOWITCH, E., *J. Chem. Phys., 7,* 551, 560 (1940).

[11] RABINOWITCH, E., "Photosynthesis and Related Processes", Vol. II-B (in preparation); Annual Review of Physical Chemistry, Vol. II, Stanford, 1951.

[12] Figures are available[1] also for productive energy consumption in 1946 and 1948. Those for 1937 were used in Fig. 3 for the sake of comparison with Fig. 2, and because the figures for 1946 and 1948 still showed incomplete recovery after the war in some countries. Following are some characteristic figures: Energy consumption for productive purposes has changed from 1937 to 1948 (estimated in billions of kilowatts),

from 911 to 1563 (+71%) in U.S.A.
from 235 to 460 (+96%) in U.S.S.R. (de facto boundaries of 1946).
from 261 to 295 (+13%) in U.K.
from 118 to 132 (+12%) in France
from 234 to 164 (−30%) in Germany (de facto boundaries of 1946).
from 89 (1936) to 74 (−17%) in Japan

THE ENGINEERING UTILIZATION OF SOLAR ENERGY

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From the inclusion in this series of papers both on the engineering utilization and on the biological utilization of solar energy, it is apparent that the scope of the present paper is to be limited to those engineering uses which do not involve plant life. A further division of the engineering field between this and the following paper has been made on thermodynamic grounds. Given a beam of sunlight to be used, one may choose either to absorb it at a blackened surface and use the resultant heat energy in more or less conventional ways; or one may seek processes dependent on the frequency of the quanta of energy which constitute the beam. The two methods may thus be contrasted as representing extremes on the scale of thermodynamic degradation. The present paper covers these methods, the first step of which involves energy degradation by absorption as heat.

One may properly ask why anyone interested in solar energy utilization bothers even to consider heat processes. The answer is that, inefficient as they are from a thermodynamic standpoint, they are today markedly better than the other class to be discussed. If mankind had to depend, starting now, on solar energy alone for heat and power, the only present alternative worth considering would be to build solar heat collectors. The objective of the present paper is to indicate roughly how far such systems now are from economic feasibility.

The effective or thermodynamic temperature of sunlight at the earth is about 6000° C. A concentrating mirror-receiving surface combination which makes the solar energy available at 1000° K. should be easy to construct; and it appears attractive since, if a heat sink is available at 300° K., a conversion to power with an efficiency of 70 per cent is theoretically possible. This is the pattern of thinking followed by substantially all the early experimenters on solar power plants, the Frenchmen Pifre, Tellier, and Mouchot and the Americans Ericsson, Eneas, and Schumann; all used a focusing mirror which followed the sun. The most highly perfected design of this type was that of Dr. Abbot[1] of the Smithsonian Institution. With a vacuum-jacketed

boiler tube at the focus of a cylindrical parabola, Dr. Abbot obtained a collection efficiency of 66 per cent and a conversion of collected solar energy to engine power of 15 per cent. The writer has estimated that an acre of such collectors in Arizona might yield 50 horsepower of continuous power;[2] that number will be considered again later.

A much simpler, cheaper and somewhat less efficient type of collector is the glass-covered flat black plate which has been studied at the Massachusetts Institute of Technology, the type of collector widely used in parts of Florida and California for domestic hot water supply.[3] It consists simply of two or three air-spaced glass plates above and parallel to a blackened metal absorber plate to which are attached tubes or fins for energy extraction in a heated water or air stream; finally, insulation under the blackened plate prevents bottom losses. The unit is mounted in a fixed position, tilted southward an amount dependent on the time of year to be favored, i.e., dependent on whether the job is house-heating, air-conditioning, or year-round hot water supply. This type of collector has been studied in sufficient detail so that it is known how outdoor temperature, desired temperature level of energy collected, latitude and atmospheric transmission affect the choice of such design variables as tilt and number of glass plates; and the engineer can predict performance in any location for which pyrheliometric records are available. Such calculations indicate, for example, that the optimum number of glass plates increases with increase in collector temperature and with decrease in solar intensity and atmospheric transmission. When the insolation is 200 B.t.u./sq. ft./hr. and the collector temperature is 80° F. above atmospheric temperature, a two-glass-plate collector is the optimum design. Figure 1 presents a group of performance curves for 2-glass-plate collectors in several localities and at various tilts. These curves will now be used to evaluate flat-plate collectors as sources of heat and power.

The Phoenix, Arizona, curve, from the calculations of Mr. Bolin,[4] shows the average performance of a collector tilted 27° southward. Since present interest is in power generation throughout the year, a tilt close to the value of the latitude, 33.5°, has been chosen. Heat sinks in Arizona are commonly slat-packed evaporative cooling towers, the performance of which indicates that 90° F. is an appropriate sink temperature to use in a Carnot efficiency calculation. Increasing the temperature level reduces the amount of energy delivered by a solar collector but increases

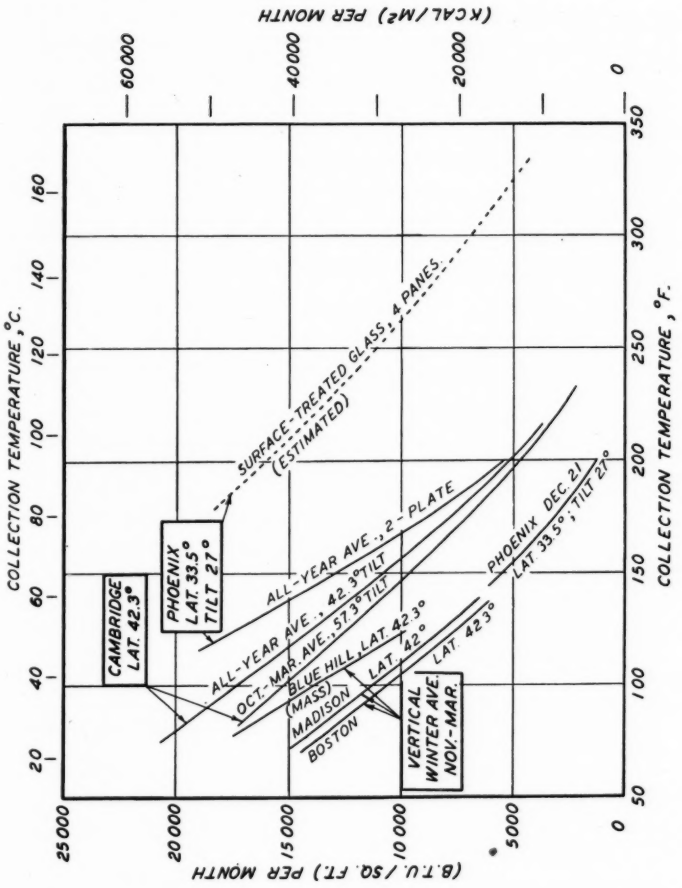

FIGURE 1. Performance of Flat-Plate Solar Heat Collectors. (Solid curves refer to use of two air-spaced glass cover plates, dotted curve to four air-spaced plates of glass treated for low surface reflection. "Collection temperature" is that of fluid to which heat is transferred; arithmetic mean of inlet and outlet is adequate approximation.)

the Carnot efficiency of the associated engine; 160° F. is found to be near-optimum, and to call for the use of 1970 square feet of collector to produce the equivalent of one kilowatt of continuous power (day and night, throughout the year). This looks hopelessly bad, and the immediate question is whether anything can be done about it. One possibility is to use glass treated for reduced reflection. Although such treatment has in the past been limited almost exclusively to optical instruments, the prospects are good that a cheap process could be developed for solar collectors if it were important. By so treating the glass that it has zero reflection at the center of the solar spectrum, the weighted-mean reflectance throughout the spectrum can be dropped from 4 to about 2 per cent. This permits doubling the number of glass plates without changing the magnitude of the incoming beam, while the outward heat losses are halved or the temperature rise above the outside air is doubled. The dotted line on Figure 1 shows a rough estimate of the effect, applied to the calculation of performance of a 4-glass plate collector in Phoenix. Using this line as before, one finds the optimum collection temperature now to be about 200° F.; and the collector area per equivalent continuous kilowatt has dropped from 1970 to 970 sq. ft.* With collectors at $1.50/ sq. ft. (optimistically low), an annual fixed charge of 10 per cent and a $15 per year fixed charge on the rest of the plant, one finds the cost of electricity to be 1.8 cents per kilowatt-hour. Actually, Phoenix is an unfortunate place to choose to put the sun in competition with fuel because natural gas is 5 cents per 1000 cubic feet, the fuel cost per kilowatt-hour is but 0.08 cents, and the estimated fixed charge is 0.26 cents, making a total of 0.34 cents (power contracts are available in Phoenix at 0.54 cents for large users). If bunker oil were used, the cost per kilowatt-hour would be 0.83 cents, still less than the solar plant by a factor of 2.2. The figures are unimpressive, but they at least indicate that we need not contemplate a cessation of industrial activity for want of power if our fuel supplies are ever exhausted.

Consider now the flat-plate collector as a source of heat rather than power. This is especially attractive when one is content with heat at a moderate temperature level such as required for

* This corresponds to 60 horsepower per acre, compared with the estimate, given earlier, of 50 horsepower with a focusing system of the Abbot type. The latter figure was rather casually calculated; it is doubtful that the value should be below that for flat-plate collectors.

space-heating or the provision of a hot water supply, because flat-plate collectors, though having a low thermodynamic efficiency for power production, are capable of maintaining a reasonably high thermal efficiency. If 100° F. is accepted as an adequately high temperature for energy for house-heating, Figure 1 indicates that for a six-month heating season, 6 x (10,000 to 15,000) or 0.6 to 0.9 x 10^5 B.t.u. of energy are available from one square foot of collector per season. For a 12-month hot water supply, 12 x (17,000 to 22,000) or 2.0 to 2.6 x 10^5 B.t.u. are available. One therm (10^5 B.t.u.) is obtainable from burning 1.2 gallons of fuel oil at 60 per cent thermal efficiency, and is therefore worth about 15 cents at present fuel oil prices. One concludes, then, that for winter heating use only, one square foot of collector saves 9-13 cents worth of fuel per year; for hot water supply, 30-39 cents. These figures are consistent with the fact that a large fraction of Miami's homes are equipped with solar water heaters.

The above calculations show that for winter house-heating the return on an investment in solar collectors would be small. To the extent that the solar heating system reduces or eliminates the fixed charge on conventional furnace equipment, an additional saving is available to add to the 9-13 cents before capitalization to find what one can afford to spend on the collector. Different individuals connected with solar house-heating projects have different degrees of optimism as to the parts of the United States in which solar heating is economically sound. It is plainly so near being competitive with fuel as to justify continued engineering studies.

In the class of heat engines but differing from those using a working fluid in the conventional way is the thermocouple as a converter of heat to electrical energy. The best that can be achieved with chromel-constantan is a 0.75 per cent useful conversion of the energy absorbed at the hot junction to electrical energy in the external circuit, when hot and cold junctions are at 420° and 20° C., respectively. Dr. Telkes at the Massachusetts Institute of Technology, seeking alloys of high thermoelectric power, low electrical resistance and low thermal conductivity—or rather, the optimum combination of those properties—has obtained 7 per cent useful conversion when operating between 420° and 20° C., when the positive alloy is zinc-antimony plus small amounts of tin or silver and the negative element is galena plus excess lead.[5] Compared to chromel-constantan with a thermoelectric power of 76 microvolts per degree Centigrade the new combination yields 330-390 microvolts, and does not deviate ex-

cessively from the normal Wiedemann-Franz ratio. The temperature level of 400° C., however, requires a focusing type of collector.

Quickly to summarize, flat-plate collectors as power generators look as promising as focusing collectors, but not promising. As sources of low-level heat they are not only promising; they have succeeded in competing with fuel in the field of hot-water heating for domestic use. The possibility of improved performance, such as by surface treatment of the glass, or of reduced cost of fabrication such as by the use of plastics, makes the flat-plate collector an important device to perfect. Solar power plants, if they could be developed in the direction of small-scale units having an efficiency comparable to large units, might find a place in our economy.

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TRANSFORMATION OF SOLAR ENERGY

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Any scientist who visits one of the deserts of this earth will be struck by the paradoxicalness of the situation: glaring sunlight burns the last traces of vegetation off the ground; but below the sand, there is water in many places that could be pumped by the same solar energy to the surface and transform the desert into a Garden of Eden. We might settle farmers all over these arid lands, if we could only equip them with black box machines that would perform economically the process of solar energy conversion.

We do not yet have such machines, and therefore it might be wise to dismiss the subject for the present. However, since this whole Conference is a meeting of scientific speculators, it may be in keeping with its spirit to pry open the Box of Pandora and to speculate about its contents.

Obviously the box will not contain anything like normal thermal machines. It is a degrading procedure indeed to take the sun radiation of about 6000° C. and to reduce it to some hundred degrees before putting it to work pushing a plunger or a turbine wheel. The maximum amount of work obtainable is given, according to thermodynamics, by the temperature drop in the machine divided by its lower temperature level. Hence, by lowering the starting temperature so drastically, we have lost about 95 per cent of our energy potential. Solar energy is a source of "high energy" light quanta; to tap it successfully we cannot follow well-trodden paths but have to develop unconventional techniques of molecular engineering.

Nature has developed such techniques in its biological processes of photosynthesis, but we should not expect to find in our black box device any algae or pine trees. A direct use or imitation of nature's photochemical approach is not the best engineering solution. The question of efficiency in biological systems is always paired with that of safeguarding the organism involved. Reactions proceed therefore in small steps, and numerous stops, detours and reversals are provided to prevent a dangerous accumulation of reaction products. Animals can get rid of excess food by a *tour de force*, but photosynthesizers have to use more subtle means to prevent overeating.

Blocked in our attempt to imitate already existing conversion systems, we have to consider the problem systematically. The box obviously has to contain an absorber for solar energy and a converter. The simplest type of absorber comprises atoms in the gaseous state, such as sodium or mercury vapor. At low pressure, they will absorb light only in very narrow spectral regions, store it for some billionths of a second as excited atoms and then re-emit it again in some arbitrary direction by returning to their ground states. Nothing has been gained or lost, only the light incident from one direction has been scattered in all directions. The atoms in their excited states have to collide with some obstacle in order for us to transform and use the trapped light quanta.

Depending on the partners involved, such collisions can have a variety of consequences. Molecules may form or split, electrons and ions may be created in the gas or at the walls, surface layers may be produced, particles of high kinetic energy may appear, radiation differing from the absorbed light may be emitted, and these reaction products may instigate consecutive reactions. We are faced at once with all the bewildering possibilities that photochemistry has to offer.

There exist, however, some ordering principles. Light, that is, electromagnetic radiation, can be absorbed only by charge carriers bound to something. The first stage of solar energy conversion leads therefore to products in which charge carriers find themselves on higher energy levels than at the outset. If, in these products, opposite charge carriers are combined in neutral molecules of reasonable stability, as in the photochemical dissociation of water to hydrogen and oxygen, we may store them and tap their energy content at will by reforming the starting material by a thermal or possibly electrochemical conversion process. If, on the other hand, we end up in this first stage of solar energy transformation with mobile charge carriers, that is, with electrons or ions, a separate storage of these reaction products is normally out of question. A bottle of electrons and one of ions would recombine with an explosion akin to that of an atomic bomb. The potential difference created by light absorption, however, can perform immediately some useful work. Thus we may distinguish between chemical converters consisting of a somewhat clumsy machinery that produces, stores and reduces chemical compounds, and more streamlined electrical converters that create and use their electric energy in a consecutive cycle.

Both types of machines have their advantages and should be developed. As far as their efficiency of conversion is concerned,

no clear-cut criterion of preference exists. In the chemical converter one will have to strive for the ideal of a complete utilization of the absorbed light quanta for the formation of new molecules without the creation of vibrational and kinetic energy. Such energy will be lost in heat and dissipated to the reaction vessel. In the electrical converter, the appearance of new charge carriers by dissociation will lead to polarization effects in the surrounding medium. This entails again heat losses that should be minimized.

The possible chemical machines vary mainly according to their reaction products, while the electrical machines show a true variety of type. The thermoelectric converter mentioned in the preceding lecture is really on its input side a thermal machine degrading the solar energy into a relatively low temperature level and using a part of it as the kinetic energy of migrating charge carriers. Its efficiency must therefore be small, and it will not be in the final competition. Not quite as clear is the situation when semiconductors form one or both of the thermocouple junctions. Light absorbed in semiconductors can create a new dissociation equilibrium of charge carriers; thus we may generate, besides a true thermo-effect, a concentration potential difference similar to that observed by Dr. Rabinowitch in solutions of ferrous and ferric ions. More promising at present appear the barrier-layer photocells, in which light absorption produces a voltage of the order of one volt by changing the space charge equilibrium between a metal and a semiconductor. Also a battery combining chemical and electrical action appears feasible in which the chemical charging of the electrodes is produced by sunlight.

Why all these machines are still in the state of wish-dreams can be appreciated when we return once more to our gas atoms. These atoms are wonderful absorbers, but only in very narrow spectral ranges. To broaden the absorption region we may increase the pressure until we approach the density of solids and liquids. However, this procedure does not merely broaden the spectral lines into wide bands, it simultaneously tends to ruin the yield of conversion. High absorption goes hand in hand with high reflection. To avoid this impedance mismatch between the atmosphere and the receiver, we have to revert to tricks such as are used in the coating of lenses or in radar camouflage.

Even after getting the solar energy into the receiver, we will find that only a small fraction serves for the conversion process contemplated. The light will be totally absorbed in a relatively

thin surface layer, hence the density of the reaction products will be so great that back-reactions take place before the partners can be separated. This seems to be the reason why our barrier-layer photocells, such as the selenium cell, traverse a maximum of response when the absorption reaches a critical magnitude. Finally, a major part of the broad-band absorption will lead to processes ending in thermal agitation. We have to gain a real understanding of the absorption spectra of solids and liquids and then to produce at will the absorption we want before a broad-band energy conversion of solar energy without excessive degradation can be attempted.

For the electrical converters we have to learn, in addition, much more about the transfer of electrons and ions through boundaries and about the formation of effective blocking layers. And finally, since the solar energy is not concentrated but spread over the earth surface, a receiver type has to be developed which can be produced for a few dollars per square meter. Electroplated metal surfaces may be the answer.

At present, physics and chemistry begin to tackle many of the pertinent problems without a side-glance at the "Sun in the Service of Man". Molecular engineering is in its infancy, but it will come to its own during this century, if "Man" in his immaturity does not destroy his own civilization.

BIOLOGICAL UTILIZATION OF SOLAR ENERGY

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So many aspects of the subject have been discussed today by experts that little remains to be added. Undoubtedly the most arresting arguments are those which concern the world's food and fuel supply. As Dr. Sax has pointed out, there are large parts of the world where the population increases at 2.5-3 per cent per year, while the average agricultural yields only increase at the rate of 1.5 per cent per year, and presumably the actual rates of increase of crops in these Group III countries are lower than the average. Since shipment of foods in the quantities required to support really large populations is scarcely feasible, this indicates that a serious food shortage will develop within about one generation.

What are the possibilities for meeting this shortage? It seems clear that the ordinary methods of agricultural research are unlikely to do so. Great improvements have already been made by the introduction of higher-yielding varieties and by the introduction of various types of disease resistance. These are responsible for the 1.5 per cent annual increase already quoted and it would be unreasonable to expect much addition to this figure. However, even if increased production could keep pace with increases in population, the places of high production would in general be far away from the most heavily populated areas, and vast shipping problems would ensue. It has been pointed out that the bringing of more tropical land into cultivation could provide important additions to our food supply, but although tropical crops are capable of growing at high efficiency, as the first two speakers have indicated, still the commonly poor soils in the tropics, as well as the inevitable development difficulties, will reduce the yields.

If a solution can hardly be expected from agriculture, still less can it be expected from forestry. On the one hand, as Drs. Raup and Pauley have shown, silviculture has only just recently reached a stage of development comparable to that of agriculture, and indeed in America it is scarcely beyond the stage of gathering from the wild. Furthermore, even when modern genetic and cultural methods are brought to bear, as in the forests of western Europe, the rate of improvement must necessarily be excessively

slow because of the long period required for the crop to reach harvest.

If one surveys the situation as a whole, it appears that the outstanding fact is the great discrepancy between the actual yields obtained from field crops and the yields measured under optimal conditions in the laboratory. As Professor Daniels has made clear, if one measures the absorbed light and the amount of photosynthesis resulting, then with *Chlorella* or other algae under laboratory conditions the yields are usually about 27 per cent of the theoretical, and there is even a possibility that they may approach 70 per cent. In contrast, the yields from agricultural crops do not as a rule exceed 1 per cent, and even in the favorable case of sugar cane, whose growth is rapid and whose product, being the total plant juice, represents a high proportion of the photosynthetic assimilation, it does not exceed 2.1 per cent. In one carefully studied case with corn (maize), if correction is made for the organic matter in the stalks, leaves and roots, and for that lost by respiration during the growing season, a yield corresponding to 1.6 per cent of the incident solar energy can be calculated. What are the factors responsible for this large discrepancy?

First of all one may consider the absorption factor. Of the visible light falling on a typical leaf, approximately 10 per cent is reflected and 10 per cent is transmitted. The transmitted light is generally absorbed by a second leaf underneath; the reflected light, since it is scattered, may be incident upon other leaves. It is evident, then, that the absorption factor does not contribute appreciably to the discrepancy.

One factor which is difficult to assess quantitatively arises from the wavelength dependence of photosynthesis. Only in the visual spectrum, and only in certain parts of this, is photosynthesis effective. Those wavelengths in the yellow and green which are not used effectively comprise an important part of the total energy incident on the leaf. Furthermore, almost any photometric measurement of solar radiation includes some ultraviolet (which is disproportionately effective on most photocells) and some infrared. It seems probable that of the incident energy measured, not more than a half can be of the wavelengths which are effective in photosynthesis.

The third consideration is of tremendous importance. The laboratory experiments with algae are made in optimum CO_2 concentrations, usually indeed in bicarbonate solutions. Land plants, on the other hand, grow in air containing no more than 0.03 per cent CO_2. It is indeed remarkable that all the world's

organic matter is produced from such an attenuated medium. Actual measurements of photosynthesis with land plants show that, when the light is bright, a concentration of CO_2 far higher than that of the atmosphere can be utilized. For wheat, photosynthesis has been shown to increase up to about 0.15 per cent CO_2, or 5 times the concentration in air. This suggests that the application of CO_2 to land plants might well be worth study. In the past a few experiments have been carried out on the provision of additional CO_2 to land plants, principally in greenhouses, but they have not been followed up. Beyond demonstrating that the procedure is feasible in a closed greenhouse, they did not prove much. Just how CO_2 could be applied to crops on a field scale is not at all clear. It has been shown that the atmosphere close to the surface of the soil, and indeed within the soil, is often enriched in CO_2 through the decomposition of organic matter by bacteria. Perhaps, therefore, some program of mulching with rapidly decomposing material, or with smoldering peat, might be investigated. In any event there is a possible field for research here. Yet, despite its great potential importance, it is to be doubted whether any serious investigation is being carried on in this field, anywhere in the world.

Fourthly, there is the temperature factor. Much of the light which falls on the leaves of crop plants finds those leaves at too low a temperature for efficient photosynthesis. Data on this are not very plentiful, especially with leaves, but older works indicate that no appreciable photosynthesis takes place at temperatures close to freezing and that, even well above that, temperature may limit the process. In the temperate zone at least, the early part of the growing season will be subject to this limitation, though it is scarcely possible to assess it quantitatively.

Lastly it must be pointed out that one important difference between the laboratory experiments on photosynthetic efficiency and the growing of crops is that the laboratory work is almost invariably done with algae. While Dr. Meier may be enthusiastic about the prospects of algae as a major crop, the problems involved in constructing the required immense areas of shallow lakes, of keeping them clean, of making up the losses of water due to evaporation and seepage, and of harvesting the crop, are staggering in themselves[1]; the education of public taste to enjoy eating algae, or else the development of some practical method of utilizing the material, involves even greater difficulties. Yet the algae do have one important advantage:—they can make contact with CO_2 (or bicarbonate) at all times. In land plants,

entry of CO_2 to the leaves is controlled by the stomata. In many plants, in average summer weather, the stomata close early in the afternoon, and as a result some of the light is wasted. In some hot dry climates, indeed, they close early in the day and remain closed until sundown. The mechanism of this has been more or less elucidated, although the ultimate causes of opening and closing are still not well understood. In general the closure is due (at least in part) to drying out of the epidermal cells of the leaf; the opening, however, is connected with metabolism and is fostered by light. If the whole process were fully understood it might become possible to maintain the stomata in the open condition during the entire day. This could hardly fail to double the photosynthetic effectiveness of the incident light when averaged over the whole growing season. Again, although this field is of great potential importance, little research on it is being carried out; perhaps as many as six or eight men in the entire world are working on this subject.

Consideration of all these factors makes clear why the average effectiveness of utilization of the sun's energy is so low. The 1.5 per cent actually observed should really be multiplied by a factor of (say) 2 for the wavelength effectiveness, 3 for the CO_2 pressure, at least 1.5 for the temperature limitation and probably 2 for the stomata. Then

$$1.5 \times 2 \times 3 \times 1.5 \times 2 = 27.$$

This gives reasonable agreement with the laboratory experiments and shows that there is no reason to believe that the process of photosynthesis is basically more efficient in algae than in land plants. It also shows that there are immense practical rewards to be gained from some well-directed pure research on the physiology of plants, not only for the light which can be shed on the workings of plants themselves, but for the increased efficiency with which such research would enable us to utilize solar energy.

[1] H. A. Spoehr has recently discussed some of the engineering problems involved in the mass culture of algae (Proc. Amer. Philos. Soc. *95*, 62-67, 1951). The water required is about a ton for each pound of dry *Chlorella*. Actual experiments on "pre-pilot plant scale" gave a conversion of solar energy of 2.5% or so.